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Electrical REVIEW

THE COVER

AMAZING GAINS in steam-turbine generator capability were realized when the modern supercharged designs were introduced a few years ago. Consolidating these gains are numerous detail design developments, some of which are covered in L. T. Rosenberg's article, "A Close Look at Large Generator Rotors," on page 26.

Allis-Chalmers Staff Photo by Frank Hart

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Let's Change Relay Time-Current Characteristics

THREE RELAYS fit in space required by one conventional induction-disc type. New relays make use of such modern components as transistors, memory cores, thermistors, and printed circuits and provide greater versatility than previously possible.

by **JOHN BAUDE**
Switchgear Department
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Overcurrent relay coordination can be simplified by reshaping the inverse time-current curves. New relays can provide desired characteristics.

UNTIL NOW, electromechanical and thermal relays have provided overcurrent protection to power systems. However, close relay coordination in modern complex power and distribution systems was often difficult because relay characteristics did not correspond to the characteristics of motors, fuses or circuit breaker trip devices.

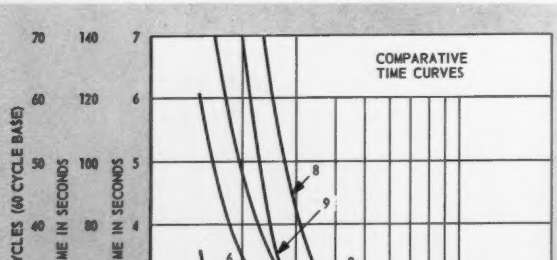
A new, completely static relay, just announced, can provide trip characteristics that can be closely coordinated with other system components.

Various inverse characteristics are offered

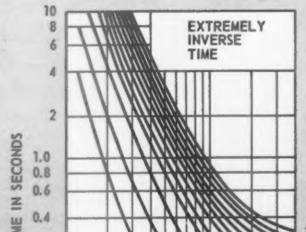
Relay characteristics have been identified by such general terms as standard, inverse, very inverse and extremely inverse. The normal inverse relay characteristics are shown in Figure 1. The curve shapes vary widely and in some cases cross over. The curves for extremely inverse relays are shown in Figure 2.

The function of an inverse time-current relay is simply to provide coordinated protection on a time-current basis for circuit breakers which do not have built-in time-current sensitive overcurrent trip devices. By means of these relays, any circuit breaker can be made to function in accordance with a predetermined relay characteristic.

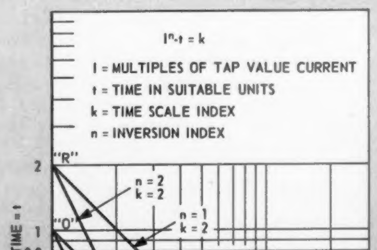
For continuity of service in a complex power distribution system, a relaying system is required to confine the effects of an abnormal system operation to the smallest area or to a minimum of feeder lines. The inverse time-current response of a protective circuit element tends to isolate an abnormally performing circuit section from the normal functioning total system. To coordinate "passive"



TIME-CURRENT CHARACTERISTICS of conventional inverse-time relays vary widely. **(FIG. 1)**



EXTREMELY INVERSE relay curves also differ from relay to relay. **(FIGURE 2)**



NEW FORMULA describes desired characteristic. New relay can match curve. **(FIG. 3)**

circuit breakers, operated by relays, with "active" circuit elements, such as fuses and circuit breakers having built-in inverse time-current tripping devices, the characteristics of each device must be considered.

New formula needed

Why attempt to solve coordination problems with a confusing plurality of time-current relay characteristics such as shown by the curves? This question was considered when developing a new overcurrent relay, and a new formula was developed to fit any situation. An ideal inverse time-current characteristic can be put in terms of the equation;

$$I^n t = k.$$

A straight line is obtained by plotting the characteristic on double logarithmic paper, as shown in Figure 3. Taking point "O" as the reference point, the time and current tap value scale would be at unity, meaning that at current tap value 1 the time value 1 could mean 1 cycle, 1 second, 1 minute, or 1 hour, depending upon the time range for which this particular protective relay was designed. For a time scale index $K = 1$, the characteristic relay curve would pass as a straight line through point "O." An increase in K would move this line in the direction shown. For a value of $K = 2$ and a tap current value of 1, the characteristic curve of the relay would pass through point R.

The inversion index n fixes the slope of the straight line, and as n increases, the slope increases, making the action of the relay more inverse with respect to time and current. The inversion index n is an expression of the degree of power which current has over time and fixes the basic characteristics of the relay.

An inversion factor $n = 2$ would approximately identify an extremely inverse relay characteristic in the region below 3 times tap current value.

The inversion index n can be used as a coordination reference, and the index to be selected depends upon the characteristics of the device with which the relay must be coordinated. Such a device might be a fuse or a circuit breaker equipped with "active" overcurrent-sensing elements. A standardization of protective devices, such as fuses and circuit breakers, should approach a coordination index similar to the one suggested for relay characteristics and should provide almost a straight-line performance.

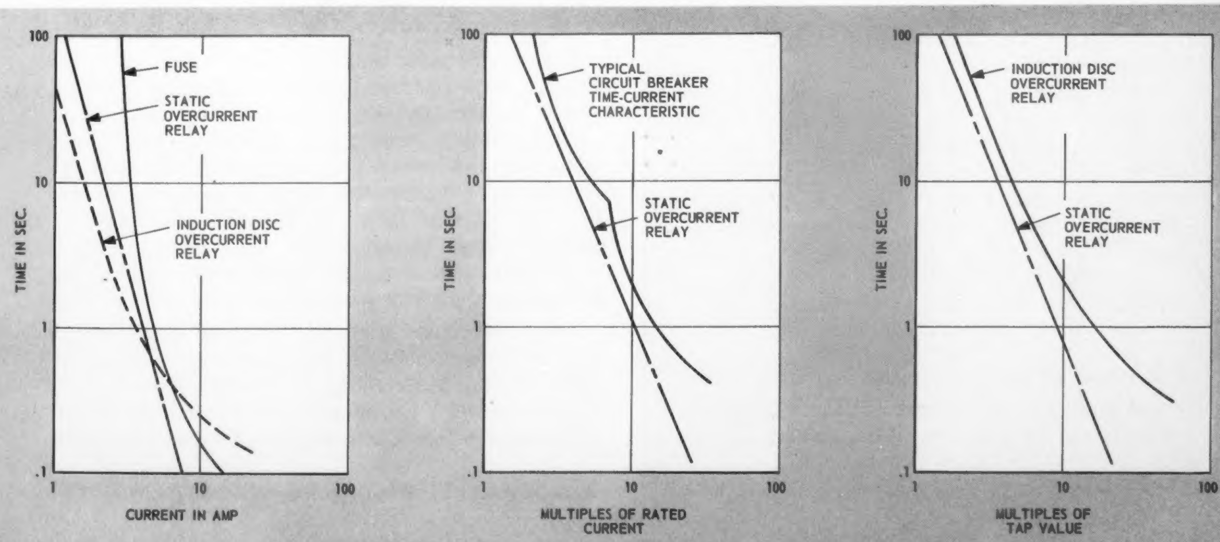
The new static-type overcurrent relay can be designed with the characteristics which, when plotted on double logarithmic cross section paper, appear as a straight line over a wide time range with an inversion factor n continuously adjustable from $n = 3$ to $n = 1$ and below.

The significance of the time index K will be appreciated when making relay time control adjustments. Changing K from 1 to 2 will move the relay characteristic performance line parallel to the original line corresponding to $K = 1$. This parallel movement of the relay performance line is equivalent to an increase in operating time proportional to an increase in the time index K. The time increase is also a function of current, and the percent time increase is a constant value for any value of K or multiples of tap current value I, as shown.

The relays can be equipped with definite minimum time limit controls, thereby fixing relay speed of response to an adjustable maximum value regardless of the magnitude of the overcurrent.

Coordination is simplified

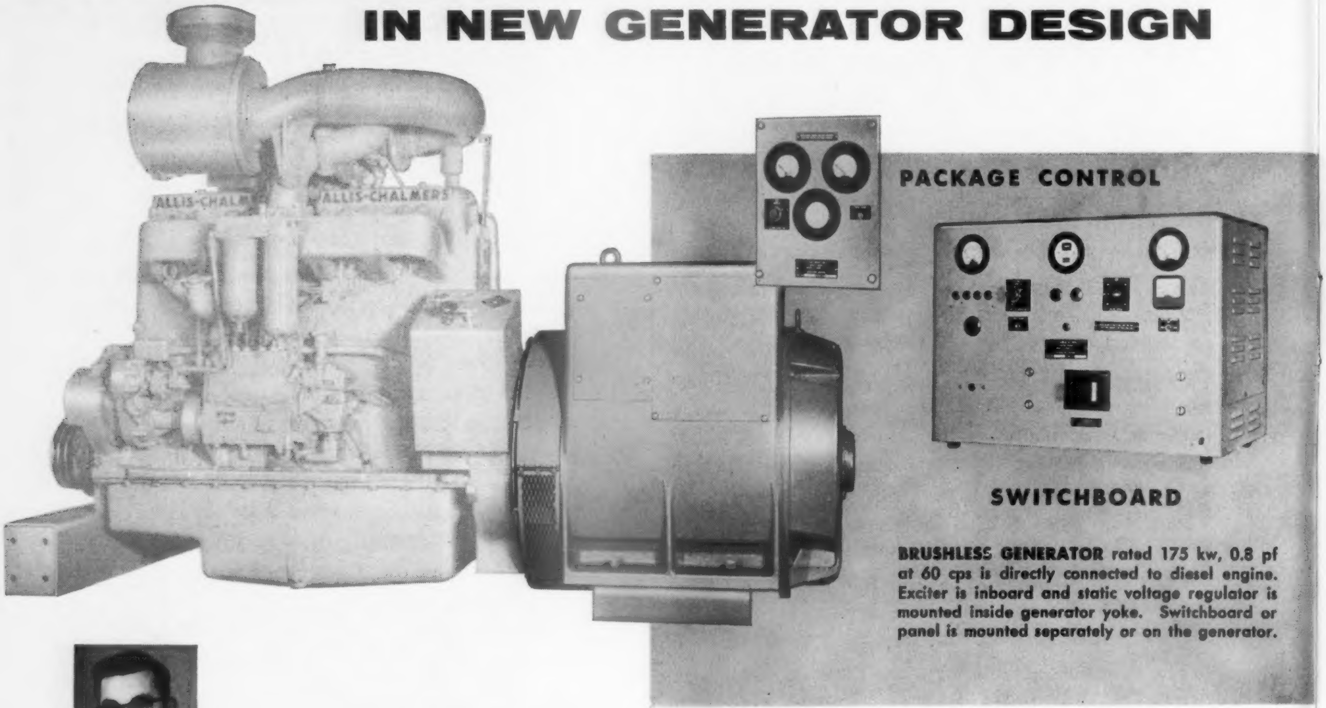
Much confusion can be eliminated in relay coordination with the help of new overcurrent relay characteristics that can be adjusted to perform in accordance with a simple mathematical function. This function can be used to explore standardization possibilities of "active" protective circuit elements and the results obtained will eventually aid the power engineer in his relay coordination and maintenance work. The curves of Figure 4 show how the new relay can be coordinated with common circuit elements.



NEW STATIC overcurrent relay can be coordinated with other system protective devices and provides maximum protection without false tripping of vital circuits. **(FIGURE 4)**

Rectifiers Replace Commutator

IN NEW GENERATOR DESIGN



BRUSHLESS GENERATOR rated 175 kw, 0.8 pf at 60 cps is directly connected to diesel engine. Exciter is inboard and static voltage regulator is mounted inside generator yoke. Switchboard or panel is mounted separately or on the generator.

by **N. VALENTINE**
Norwood Works
Allis-Chalmers Mfg. Co.
and
W. G. NOLTE

Engine-generator set runs without sliding contacts. Silicon rectifier circuit eliminates brushes, commutator and slip rings.

ENGINEERS HAVE LONG SOUGHT to eliminate sliding contacts in electrical machinery. Since engine-driven generators are being used as primary power sources in progressively greater extremes of climate and environment, the need to eliminate the troubles relating to brushes, commutators and slip rings has increased. Generator designers have selected materials and made performance allowances for many extreme operating conditions. Insulation materials and protective coatings have kept pace with environmental needs, but until relatively recently no practical solution was found to eliminate sliding contacts — the generator's "Achilles' heel."

Regulation of early machines was a problem

Several possibilities have been considered that eliminate the commutator and brushes. Permanent magnets may be used to establish constant field polarities. However, permanent magnet generators must be larger than the usual machine because permanent magnets with sufficient magnetic energy, retentivity and permeability to withstand the demagnetizing effects of starting inrush currents or momentary short circuits have not yet been developed. A conventional machine can be excited to compensate for load reaction, but there is no simple way to regulate a permanent-magnet generator. For good voltage regulation either the non-regulated permanent-magnet generator must be underrated, or a nominal sized machine must be used with a capacitive load compensator similar to the arrangement in Figure 1.

Inductor alternator designs have substituted static rectifiers for brushes and commutator. The rectifiers convert part of the alternator output to excite the alternator field circuit. Inductor alternators are made in two basic forms, homopolar and heteropolar, differing basically from the conventional and permanent-magnet ac generators because their exciting windings are wound on the stator with the power windings. Voltage is induced by causing a variation in the permeance of the mutual flux paths between the excitation and power windings.

The more recent heteropolar inductor alternator has superseded the homopolar design because of its lower cost, lighter weight, better voltage regulation and more rapid response than the homopolar unit. In spite of the improvements in the heteropolar inductor alternators, with

their greater utilization of material and faster response to load corrective control, they cannot compete with conventional generators in delivering 50 to 60-cycle power. Because inductor alternators produce power by air gap permeance variation, they are too sensitive to load reaction. To maintain acceptable voltage regulation, high field excitation must be used to produce the rated flux densities in an air gap made large enough to offset the demagnetizing effects of load reaction.

The inductor alternator is more competitive with conventional ac generators at medium and high frequencies (400 to 50,000 cycles). At high frequencies it becomes increasingly difficult, in the conventional machines, to provide space for a full complement of rotor and stator windings with their respective insulation, since the number of poles are increased as the operating frequency increases. Although inductor alternators have eliminated brushes, they have not provided satisfactory solution, because their cost, size and unflexible performance do not compare favorably with the conventional ac generator. In earlier days designers probably concluded that sliding contacts were a necessary evil for which there was no acceptable substitute and, at best, only partial or no cures.

Silicon rectifier made design possible

When copper oxide, selenium, and germanium rectifiers were developed, the question arose — could a rectifier assembly, made of these cells, be used on the shaft of a generator in place of the commutator of an integrally-mounted exciter? A patent on such a scheme was issued in 1934, but although the concept was sound, the rectifiers available at the time could not fully utilize the idea.

Only since the development of silicon power rectifiers could the potentialities of a brushless ac generator be realized. Table I compares the operational characteristics of a typical medium power silicon diode with a germanium diode and a selenium rectifier cell. All rectifiers tested had 4 by 4-in. heat sinks, fan-cooled with approximately 200 ft per minute air velocity.

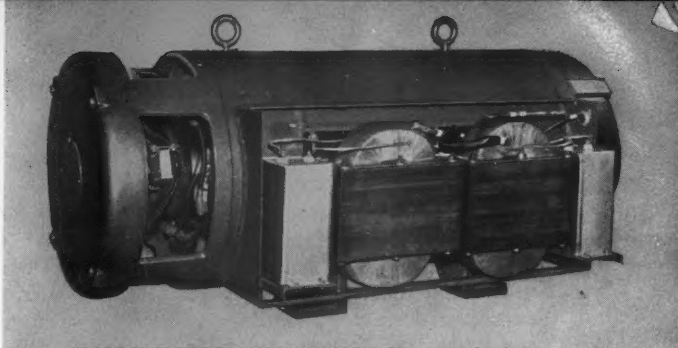
TABLE I

Comparative operational characteristics of silicon and germanium diodes and selenium cells.

	Silicon diode	Germanium diode	Selenium cell
Maximum allowable temperature for full rating	150°C	85°C	100°C
Maximum allowable peak inverse voltage	600	70	36*
Maximum continuous direct current at maximum allowable cell temperature	12 amps	12 amps	4 amps

* Selenium cells are rated at rms applied voltage

The characteristics in Table I indicate that a given size silicon diode can handle 8.5 times the power of a germanium diode and approximately 35 times the power of a selenium cell. Therefore, a rectifier assembly of silicon diodes can be made small enough and with high enough rating to be substituted for the commutator of a conventional exciter as shown in Figure 2. When the exciter armature is mounted on the generator shaft the excitation



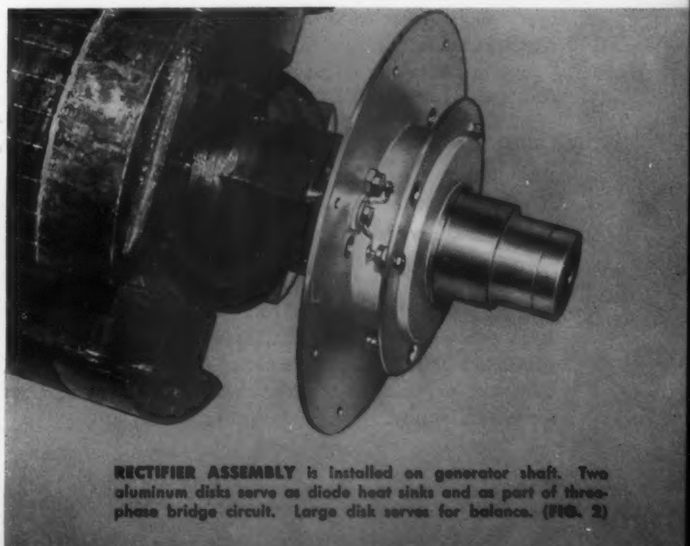
CAPACITIVE LOAD COMPENSATOR holds terminal voltage to within specified limits when the armature reaction, resulting from loading a 5-kw 1800-rpm generator, causes field demagnetization. (FIGURE 1)

is delivered from the exciter through the rectifier, to the generator field coils without sliding contacts. Figure 3 is a typical brushless generator rotor. The brushless generator retains the characteristics of a conventional machine, but it is free of brushes, commutator and slip rings and their attendant difficulties. Conventional and brushless rotors of equivalent rating are compared in Figure 4.

Silicon power diodes in electrical machinery involve electronic design considerations. Input and output of various rectifier circuits must be evaluated to make the best use of the exciter and the diodes, and voltage and current transient conditions must be analyzed to avoid diode failures. Diode volt-ampere characteristics must also be examined to establish quality standards and to insure reliable service. A typical brushless generator scheme is shown in Figure 5.

Bridge circuit provides excitation

The full-wave, three-phase bridge circuit is the most desirable arrangement for maximum reliability and utilization of the exciter and rectifiers because the circuit has the minimum Epiv/Edc voltage ratio (1.05) for the maximum Edc/Erms voltage ratio (1.35). The half-wave, three-phase circuit reduces rectifier costs, but with this system the diodes are subject to twice the peak inverse voltage for the same dc output voltage. The use of the half-wave circuit is limited because of the relatively wide range of operation required to excite the generator, since normal generator field excitation voltages will range from 30 volts at no load to 150 volts when line-starting a full-



RECTIFIER ASSEMBLY is installed on generator shaft. Two aluminum disks serve as diode heat sinks and as part of three-phase bridge circuit. Large disk serves for balance. (FIG. 2)

capacity induction motor load (0.35 to 0.4 hp per kw of generator rating). The normal operating field voltage will be approximately 90 volts at rated generator load.

Rectifier peak inverse voltage is increased by an effect called "overlap" or commutation. Overlap occurs when two diodes in different phases conduct current simultaneously in the course of transferring the dc load current from diode to diode. The overlap time would be zero if the power source internal impedance were resistive or zero; however, in practical cases the impedance is inductive. Consequently, the overlap time interval depends upon the reverse-current transient time constant of the combined power source diode loop. Observations of this phenomenon with a typical brushless exciter show the overlap interval to be in the order of microseconds. However, the amplitude of theoretical peak inverse voltage across the non-conducting diodes is approximately doubled by the addition of the "commutation spike" to the normal wave form. This commutation spike will cause diode failures if sufficient allowance is not made in designing for the range of generator excitation voltage and selecting diode peak inverse voltage ratings.

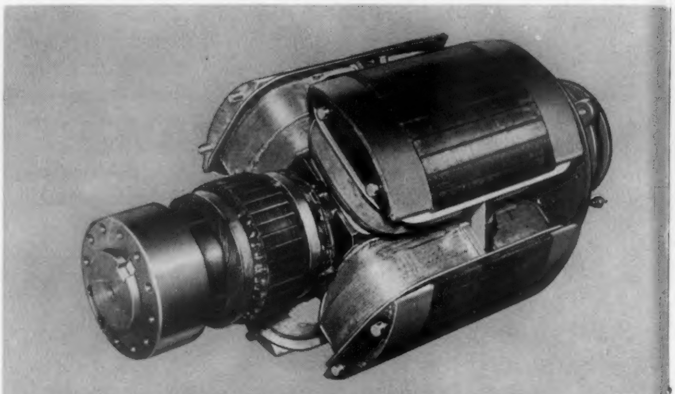
When diodes are used to supply a typical generator field, they should have a 300-volt peak inverse voltage rating for a three-phase full-wave bridge and 600-volt peak inverse voltage rating for a three-phase center-tap circuit. Although silicon diodes are commercially available in rating up to 600 volts, the more conservative three-phase bridge circuit is recommended because of its greater reliability, since diodes with the higher peak inverse voltage ratings may have shorter life expectancy.

Since the brushless exciter affords no means of direct self-excitation as does a conventional dc exciter, consideration must be given to the best means for self-exciting the generator-exciter unit. The input-output characteristics and time constants of exciter, generator and feed-back network are carefully coordinated to assure automatic voltage build-up and stable operation of the system. To provide complete reliability, the generator voltage is regulated by a magnetic amplifier circuit that matches the generator characteristics.

Trouble-free operation is assured

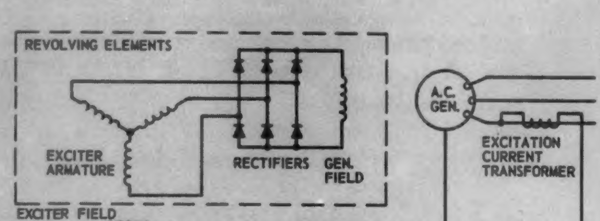
Engine-driven generators serve as sources of primary power all over the world. The continuing operation of every one of these installations depends on brushes, commutators and slip rings. In the tropics, in desert areas, in corrosive and abrasive dust laden atmospheres, slip rings, commutator segments and brushes are subject to excessive wear and damage. Many man-hours are spent in maintaining these components. Possible commutator and slip-ring sparking prohibits the use of a conventional generator in combustible or explosive atmospheres.

Brushless generators, on the other hand, are not dependent on mechanical rectification and will therefore operate dependably in areas where conventional units are less reliable. Present designs of brushless generators evolved from a series of developments such as permanent-magnet generators and inductor alternators. The resulting design made the elimination of commutation in a generator set a practical reality.



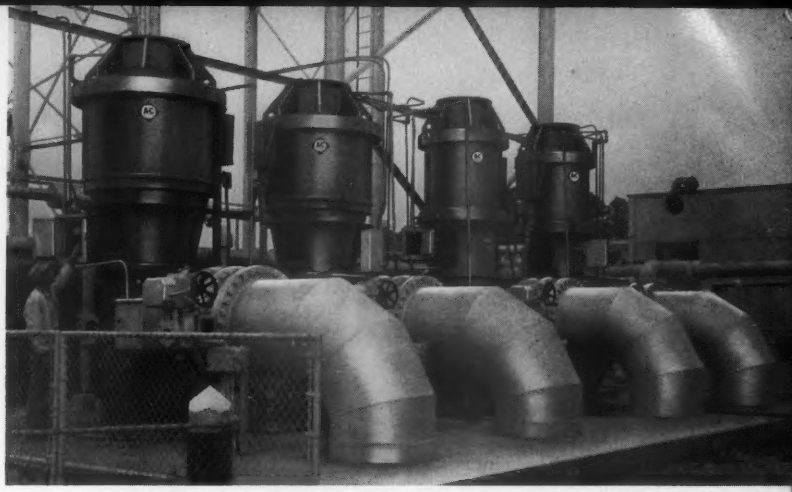
BRUSHLESS GENERATOR ROTOR, viewed from the engine coupling end, is shown to be similar to the rotor of a wound-rotor motor. **(FIG. 3)**

CONVENTIONAL ROTOR when compared to a brushless rotor indicates space saving and the use of fewer parts with the brushless excitation scheme. Both rotors are for 60-kw, engine-driven generators. **(FIG. 4)**



RECTIFIED DC directly excites the three-phase generator field. Static voltage regulator output is field excitation. **(FIGURE 5)**

CHOOSING PUMP MOTORS



SPEED-TORQUE CHARACTERISTICS and operating procedures of these pumps may have affected motor design. Large installations require careful matching of motor torque and pump characteristics.

by **R. L. BROWN**
Centrifugal Pump Dept.
Allis-Chalmers Mfg. Co.

Operating conditions in addition to load demand affect the motor ratings applied to pumps. Here are some of the factors governing motor selection.

NORMAL PUMP LOAD is a prime consideration in selecting a particular size motor for a pump application. However, the type of pump and the method of starting will very often influence the selection of the drive motor, control, and protective device settings.

The pump type is usually considered to be centrifugal, mixed, or axial flow, but these conditions are not distinctly separate types. There is a continuous transition in impeller and case design from centrifugal through mixed to axial flow. To closely define a pump type the pump designer adopts a parameter called specific speed* which depends upon the quantity and head pumped at a given rotational speed.

To simplify the starting considerations, pump operation can be divided into three groups: starting against a closed discharge valve, starting against an open discharge valve, and complex starting.

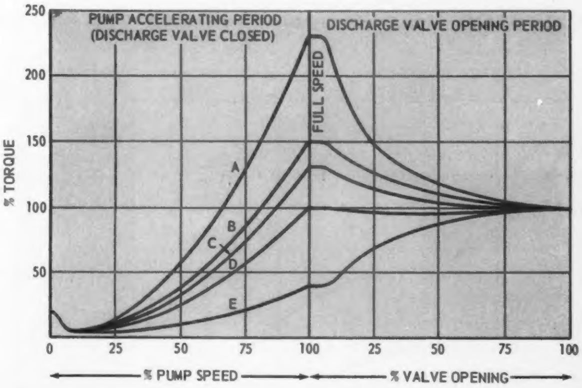
Shutoff torque determines motor design

Pumps of low and medium specific speed, which includes all the centrifugal and some of the lower specific speed mixed-flow designs, are normally started against a closed discharge valve. Occasionally higher specific speed pumps of the mixed and axial-flow type are started against a closed valve, but the practice is avoided whenever possible.

The curves in Figure 1 are typical pump speed-torque curves for five axial, mixed and centrifugal types of various specific speeds. The torque curves are square law curves from abour 10 percent speed to 100 percent speed. Initial breakaway torque is not easily determined and varies with pump size, type of bearings, stuffing box and time elapsed since the previous run. With most pumps this breakaway torque normally lies between about 15 to 25 percent of full-load torque and rapidly drops to meet the torque curve

* Specific speed: $N_s = \dfrac{N\sqrt{Q}}{H^{3/4}}$

where N = rpm
Q = gpm
H = total head in feet



STARTING PUMPS against a closed discharge valve, accelerating to full speed, and then opening the valve shows how pumps of different specific speeds approach their normal operating points. **(FIG. 1)**

Curve	Type of Pump	Specific Speed	BHP & Torque At Shutoff
A	Axial Flow (Diffuser)	10,000	230%
B	Mixed Flow (Diffuser)	6,500	150%
C	Mixed Flow (Diffuser)	6,500	130%
D	Mixed Flow (Volute)	5,000	100%
E	Centrifugal	1,250	40 %

Note: C is special design to reduce shutoff BHP but with some sacrifice to other desirable characteristics.

100% BHP and torque are at rating which is assumed to be best efficiency point on pump head-quantity curve.

produced by the hydraulic characteristics of the pump. At about 10 percent speed the mechanical considerations which are important in determining the breakaway torque are no longer of any real significance compared to the hydraulic torque.

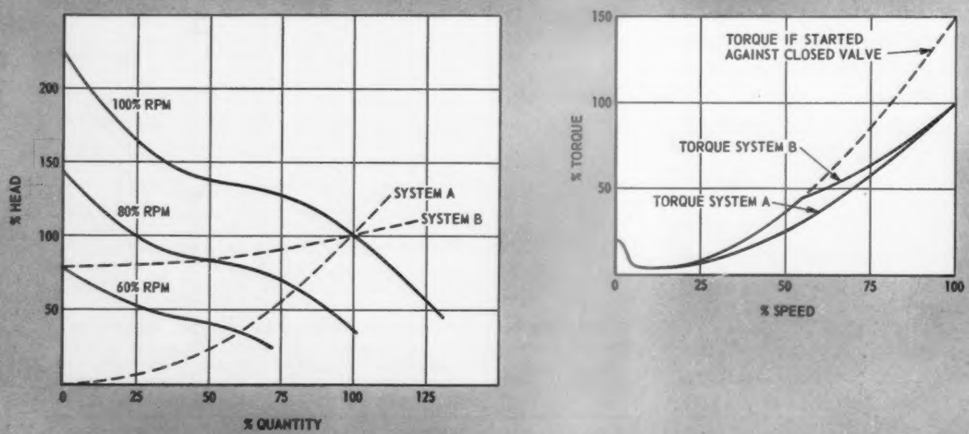
When the pump reaches full speed the discharge valve is opened. The shape of the torque curve from the point at which the discharge valve starts to open and its fully open position will vary, depending upon the characteristics of the system and the valve. The inertia of the water in the pipeline will also have some effect on the shape of this portion of the torque curve. Three types of valves are normally used on pump discharge lines: cone, gate and butterfly valves. Each type has a different characteristic which will affect the shape of the torque curve during the period of valve opening. However, the torque will always continuously approach 100 percent. The time required to move the valve from fully closed to fully opened position may depend upon a number of factors, such as the surge characteristics of line and the mechanical forces required in moving a large gate from one position to another. Generally, the time required to open a large valve is from about 20 seconds to possibly 3 or 4 minutes. It is possible to have a continuous family of speed-torque curves lying between curves *A* and *E* in Figure 1, depending first upon the specific speed, and second upon the design of the pump impeller and casing.

Pumps start with open discharge valve

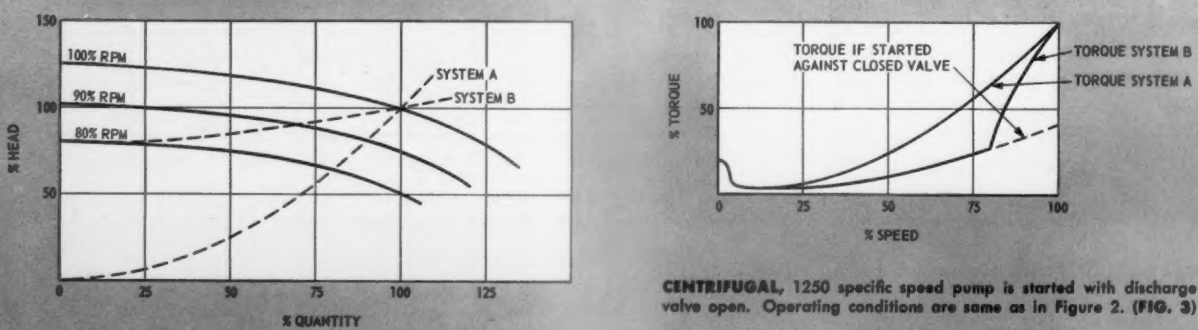
With a check valve in the discharge line to prevent reverse flow, the speed-torque curve will rise continuously from about 10 to 100 percent. At 100 percent speed the pump will operate at its rating and the torque will therefore be 100 percent. The shape of the speed-torque curve from the 10 percent speed point to 100 percent speed will vary, depending upon the characteristics of the system.

A family of head-quantity curves for a typical mixed-flow pump at a specific speed of 6500, together with two possible system curves, *A* and *B*, are shown in Figure 2. With a completely frictional system such as *A*, the system curve itself is square law and will always lie on the best efficiency point of a family of head-quantity curves. Therefore, the speed-torque curve must also be a square law curve. With system *B*, where there is an 80 percent static head component and a 20 percent frictional head component, the pump speed must rise to 60 percent before the pressure developed is sufficient to push water into the system. From zero speed to 60 percent speed, the torque curve will follow the curve already indicated for starting against a closed discharge valve. At 60 percent speed the pump will start to deliver water and the torque will then rise to the 100 percent torque, 100 percent speed point.

Figure 3 shows a similar example for a centrifugal pump of 1250 specific speed. The system curves are the same as before, but in this case, because of the low shutoff head of a centrifugal pump as compared to a mixed-flow pump, the speed must rise to 80 percent before the head generated is sufficient to overcome the static head of the system. Between the conditions of Figures 2 and 3 there must be some pump at which the torque curve will be the same for completely frictional systems and those with static head components. The pump shown in curve *D* in Figure 1 meets the condition in which the brake horsepower and torque at shutoff is the same as that at the output rating. These examples neglect the effect of inertia in the pipeline which will simulate a partially closed valve situation.



MIXED-FLOW, 6500 specific speed pump is started with discharge valve open. System *A* has all friction head; system *B* has 20 percent friction and 80 percent friction head. (FIG. 2)



CENTRIFUGAL, 1250 specific speed pump is started with discharge valve open. Operating conditions are same as in Figure 2. (FIG. 3)

Operating conditions are many and varied

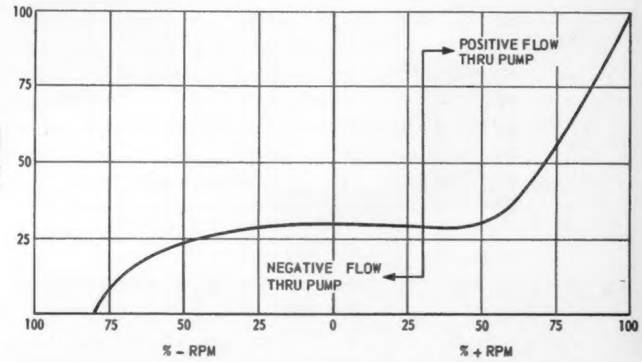
Complex starting is not used in the majority of pump installations. It is usually confined to mixed and axial-flow pumps which have a high brake horsepower at shutoff. Special techniques occasionally must be used when there is high brake horsepower at shutoff or when system conditions prevent starting a pump with an open discharge line. Complex starting procedures depend on system requirements, but in general the following factors are considered.

1. A reverse rotation rachet fitted to the motor might be necessary.
2. Check valves fitted on the pump discharge lines may be required.
3. The opening speed and characteristics of the discharge valve should be known.
4. If there is reverse flow through the pump to be started, is the flow coming from the system, from another pump, or from a series of pumps? The characteristics of the reverse flow should be known.
5. The head-torque characteristics of the pump to be started in reverse rotation (runaway speed from 0 to 100 percent rpm) must be known.

A typical complex starting problem is a condenser circulating water installation with two axial-flow pumps which normally discharge in parallel through the condenser cooling system. To lower installation cost and reduce head loss on the system, check valves may not be fitted on the pump discharge lines. If one pump is operating and discharging in the system, it may be necessary to start the second pump. If the pump is started with the discharge valve closed, the motor will become overloaded because of the high shutoff brake horsepower. If the pump is started with the discharge valve open, the pump already operating will deliver into the cooling system and also back through the presently idle pump. The water flowing through the idle pump will cause reverse rotation if a nonreverse rachet is not fitted; also the discharge of water into the cooling system will be reduced with a resulting adverse affect on the condenser vacuum. It is possible to start opening the discharge valve at the same instant the pump is started or slightly before the pump is started. Rate of acceleration of the pump, the speed of opening the valve, and the frictional characteristics of the valve all become important factors. Figure 4 shows a typical speed-torque curve for an axial-flow condenser circulating pump from runaway speed through 100 percent rpm. The curve is based on a 10,000 specific speed pump starting with discharge valve open and with an identical pump delivering both into a complete frictional system and through the presently idle pump.

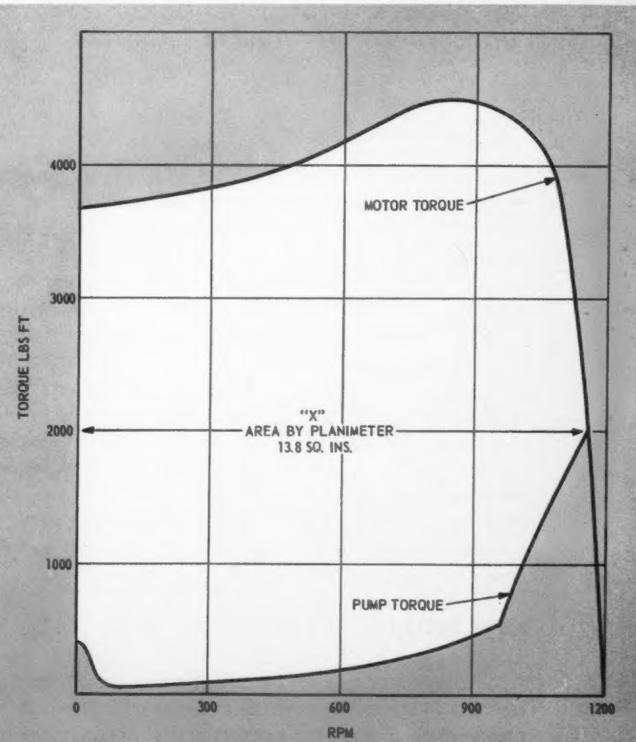
Excess torque determines acceleration time

The net torque available for accelerating the pump-motor unit will be the difference between the motor speed-torque curve and the pump speed-torque curve. A typical pump-motor combination is shown in Figure 5. The accelerating time in seconds is computed according to the following relationship: $t = Wk^2 \times \text{rpm}/308T$, where T is the average accelerating torque derived from curves similar to those in Figure 5. The Wk^2 of the pump is usually small in relation to the motor. For a small pump at high speed the Wk^2 is usually about 10 percent of the motor. For the larger units the Wk^2 may increase to about 20 percent of that of the motor. When applying a motor to a pump operating against a closed discharge valve, make sure that it can accelerate the pump in the required time without overheating. In starting with an open discharge valve and in selected complex starting situations, an examination of applicable speed-torque curves will indicate a satisfactory motor design.



TYPICAL SPEED-TORQUE shows 10,000 specific speed axial-flow pump starting with the impeller in reverse rotation. **(FIGURE 4)**

STARTING TIME for a pump-motor is calculated from net average accelerating torque. Use any method to find the area. **(FIGURE 5)**

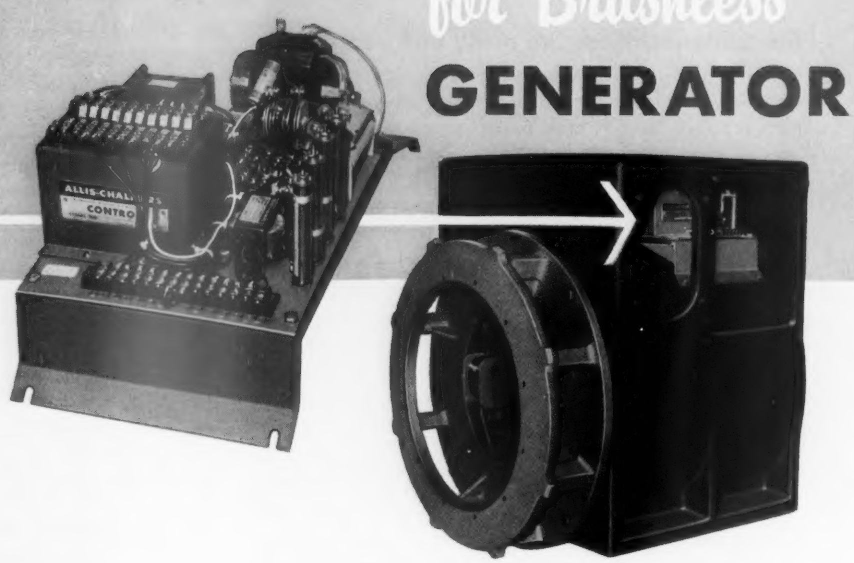


$$\text{Average distance between curves} = \frac{\text{Area}}{\text{Length "X"}} = \frac{13.8}{3.875} = 3.57''$$

Torque scale $1'' = 1000$ lbs/ft

Then average accelerating torque is $3.57 \times 1000 = 3570$ lbs/ft

STATIC REGULATOR *for Brushless* GENERATOR



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ALL STATIC REGULATOR COMPONENTS are mounted on single panel. Assembly is small and compact. When installed in the generator stator housing, the regulator makes a complete brushless generator package. This static regulator can be used from 40 to 300 kw.

New static regulator matches brushless exciter characteristics. Design provides operating flexibility and improves generator voltage regulation.

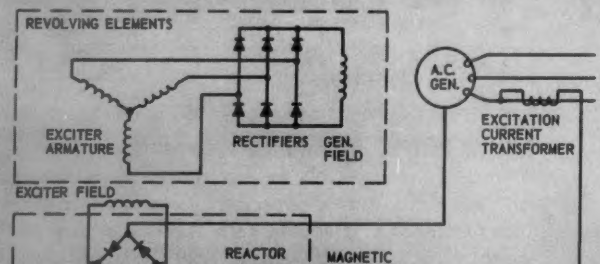
INCREASINGLY SEVERE INDUSTRIAL and military applications requiring close control and regulation of output voltage prompted the development of synchronous generators with brushless exciters. Exciter field control must be provided by an automatic voltage regulator which maintains generator voltage output in spite of load changes, machine heating, ambient temperature changes, prime mover speed changes and other disturbances. The static magnetic-amplifier voltage regulator meets these requirements and can withstand adverse environmental conditions. Although designed for the brushless exciter, the static unit will operate satisfactorily with conventional machines. The design supplements the *Rocking Contact* electromechanical voltage regulator, which since its introduction has continued to set industry standards for this class of equipment.

Static regulator has no moving parts

The magnetic-amplifier circuit makes possible a static voltage regulator that eliminates all maintenance normally associated with electromechanical devices. Magnetic amplifiers with their saturable reactors and semi-conductor rectifiers have a high degree of reliability, and proper circuit design makes use of their characteristics to the fullest.

Development of the voltage reference circuit, an integral part of the complete voltage regulator, included an investigation of several devices such as gas tubes and resistance bridges. Cold cathode gas tubes have been widely used as voltage reference sources and are somewhat more reliable than high-vacuum electron tubes, but the gas tubes still require periodic inspection and replacement. Non-linear resistance bridges incorporating various types of non-linear resistive elements are another source of a voltage reference or comparator circuit. Although bridges eliminate electron tubes, they require special compensation to remain accurate during temperature variations.

The static regulator for this brushless machine uses a Zener diode as the voltage reference. This silicon diode is specially designed to maintain an extremely stable inverse-



THREE-PHASE EXCITER ROTOR output is rectified by semi-conductor rectifiers mounted on the generator shaft. The rectified dc is directly connected to excite the three-phase generator field. The voltage regulator magnetic amplifier, energized by the synchronous generator, provides excitation for the brushless exciter field. **(FIGURE 1)**

voltage characteristic. It has the reliability inherent in semi-conductor devices and is stable over varying frequency and temperature conditions.

The brushless exciter-generator scheme illustrated in Figure 1 replaces the usual dc exciter, commutator and generator slip rings. Initial build-up of voltage is usually obtained from the residual voltage of the exciter and generator. Magnetic-amplifier rectifiers normally have a forward voltage drop low enough to develop excitation current and cause voltage build-up when the generator is started.

A field "flashing" circuit provides excitation current from a separate source if the voltage does not build up. A blocking rectifier prevents back feed of the excitation voltage if the flashing pushbutton is accidentally depressed after generator voltage is built up. This build-up phenomenon is analogous to that of a self-excited dc machine, which requires "flashing" if its residual voltage is lost.

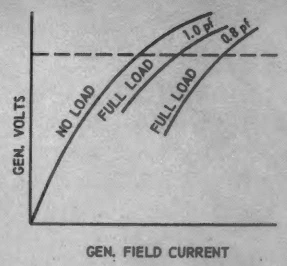
The generator characteristics shown in Figure 2 could be plotted as a function of exciter terminal voltage by changing the scale units and neglecting the effect of generator field heating. The curve can also be plotted as a function of exciter field current if exciter non-linearities, such as saturation and residual voltage, are neglected. With the generator at no load the generator induced and terminal voltages shown in Figure 3 are identical ($e_i = e_t$). To maintain constant terminal voltage under load, the generator induced voltage must be increased to compensate for the synchronous reactance (IX_d) voltage drop. The relationships are shown single phase, but they also apply to the three-phase machine.

Fast response is assured

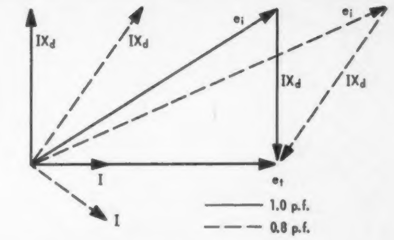
A compensation circuit provides approximately correct excitation for rapid transient response, high motor-starting capability, and accurate voltage regulation. The voltage regulator output is then superimposed to adjust the excitation to the required value.

The generator load establishes the phase relationship between generator terminal voltage and the load current. The voltage e_{ct}, in Figure 4*a*, induced in the excitation current transformer secondary, is directly proportional to the magnitude of the load current, and is vectorially 90 degrees ahead of the magnetizing load current I. The generator terminal voltage e_t is common to Figures 3 and 4. With the secondary voltage e_{ct} made equal to the generator synchronous impedance drop IX_d, the resultant voltage e_f of the excitation system compensation circuit then becomes equal to the generator induced voltage e_i. Since the exciter field current i_f, proportional to the excitation voltage e_f, is the quantity which produces generator induced voltage e_i, a compensation circuit can correct generator terminal voltage for the effect of load. However, this circuit can provide only coarse voltage regulation, over the extremes of operating conditions.

Control of the magnetic amplifier, which alters the relationship between excitation voltage e_f, and actual ex-



SYNCHRONOUS generator characteristics, plotted as terminal voltage against generator field current, are directly related to exciter voltage and current. **(FIGURE 2)**

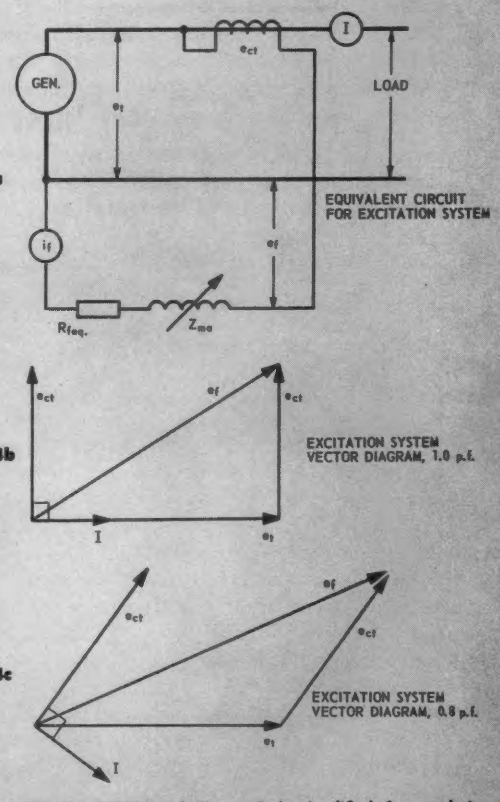


GENERATOR VECTOR diagram shows relationships of generator terminal voltage e_t, synchronous reactance X_d, current I, and the generator internal or induced voltage e_i. **(FIGURE 3)**

Fig. 4a

Fig. 4b

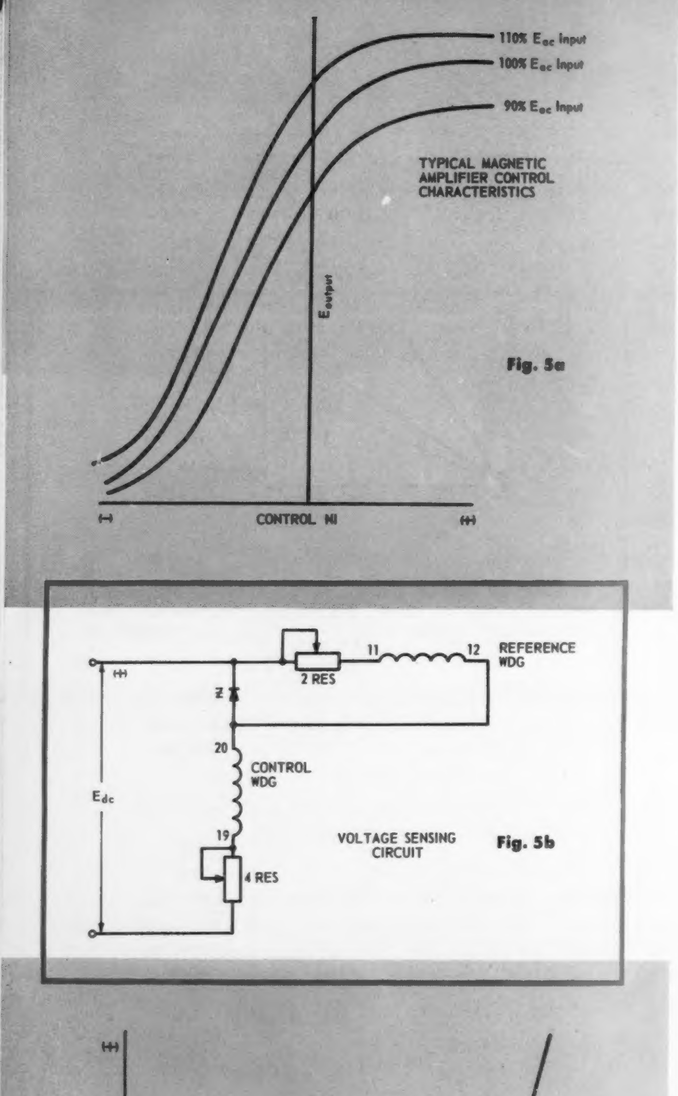
Fig. 4c



EXCITATION SYSTEM of Figure 1 is simplified for analysis, with bridge rectifier and exciter field represented by an equivalent ac resistance $R_{f_{eq}}$, and magnetic amplifier and its self-saturating rectifiers as an equivalent impedance Z_{ma}. **(FIGURE 4)**

Symbols for Figures 3 and 4

e_{ct}	excitation current transformer secondary voltage	IX_d	generator synchronous reactance voltage drop
e_f	excitation circuit voltage	$R_{f_{eq}}$	exciter field equivalent ac resistance
e_i	generator induced voltage	X_d	generator synchronous reactance
e_t	generator terminal voltage	Z_{ma}	magnetic amplifier equivalent impedance
I	generator line current		
i_f	exciter field current		



MAGNETIC AMPLIFIER, characteristics shown in A, controls generator. Voltage is applied to voltage-sensing circuit B. Net output (net *NI*) in C of voltage-sensing circuit is resultant of the reference ampere-turns (ref. *NI*) and the control ampere-turns (control *NI*). (FIGURE 5)

citation current i_t to the brushless exciter, improves the regulation effected by the compensation circuit. For purposes of analysis, the reactor and its self-saturating rectifiers may be considered as a variable impedance which controls the dc output voltage of the bridge rectifier.[1]

The magnetic amplifier is connected so that direct current through its control windings changes saturation of the core. Output is increased when the core is saturated by control current. The magnetic amplifier responds to the net ampere-turns (*NI*) of dc control (the sum or difference respectively depending upon polarity of the products of the current and the turns of the various control windings). Typical magnetic-amplifier control characteristics are shown in Figure 5*a*.

Zener diode maintains voltage control

The voltage-sensing circuit translates the rms value of the generator ac voltage into suitable dc intelligence signals to control the magnetic amplifier. This circuit is usually a bridge rectifier which converts the ac voltage to a dc voltage proportional to the average value of the ac wave. Such use of rectified dc makes the regulating system independent of the frequency of the generator voltage.

The single-phase sensing in this regulating system is accomplished from the line-to-line voltage, since the line-to-neutral voltage is subject to third harmonic distortion in Y-connected alternators.

The voltage-sensing circuit is energized from step-down transformer *1T* connected line to line across the generator low voltage windings. This circuit along with that of the complete regulating system is shown in Figure 6. The output of transformer *1T* is applied to rectifier *1REC* that energizes a dc voltage divider circuit composed of resistor *3RES* and voltage-adjusting rheostat *1RH*.

The voltage-sensing circuit itself is made up of resistors *2RES, 4RES* and silicon Zener diode *Z*, which provide output signals to control windings on the magnetic amplifier as shown in Figure 5*b*.

Actual voltage sensing or measuring is accomplished by the Zener diode. This silicon diode is operated in the saturated region of its inverse characteristic, and once the saturation voltage is reached, essentially a constant voltage is maintained across the device over a wide current range. Ratings of the Zener diodes in this static voltage regulator exhibit extremely low temperature coefficients.

The voltage across the Zener diode is fed through resistor *2RES* into magnetic-amplifier reference winding 11-12 in a direction to obtain ceiling excitation. The characteristics of this circuit are shown in Figure 5*c*. The generator excitation increases until the saturation level of the Zener diode is reached, causing current flow to increase through winding 19-20 in a direction to decrease excitation. The magnitude of the control current is adjusted with resistor *4RES*. The operating point is reached when the net ampere-turns (*NI*) in the control winding are equal to, or slightly larger than, those of the reference winding.

System operation is stable

A damping or stabilizing signal results from the rate of change of current in the exciter field. Since the primary winding of damping transformer *DT* in Figure 6 is connected in series with the exciter field, its secondary voltage is proportional to the rate of change of primary current. Resistor *1RES* controls the damping signal which is applied to magnetic-amplifier control winding 5-6.

Assume the generator voltage decreases as a result of application of a load to the generator. The increase in load current raises the secondary voltage of *XCT*, which increases the supply voltage to the magnetic amplifier and results in an immediate increase in excitation voltage to return the generator voltage to normal. At the same time, as a result of the generator voltage decrease, the dc voltage decreases at the voltage-sensing circuit. The reference voltage across the Zener diode remains constant and the current through the Zener diode decreases. The net control ampere-turns are changed in a direction to raise the magnetic-amplifier output, which further increases excitation to correct the generator terminal voltage to the desired value. The opposite effects occur on a rise of generator voltage resulting from a decrease in load.

The greater part of excitation change as a result of load (by far the largest system disturbance) is accomplished with the compensation circuit of *XCT*. With this scheme, the voltage regulator has to correct or trim the excitation level for only such minor disturbances as the inexactness of the compensation circuit, field heating of exciter and generator, saturation of the exciter, and frequency or speed changes of the prime mover.

Extremely rapid transient performance is attained, since the compensation circuit response is instantaneous and the basically rapid response of the magnetic amplifier is obtained with a relatively low gain regulator circuit. Excellent voltage regulation results without the system stability problems and additional complications of a high gain multiple-stage uncompensated regulator.

Cross-current compensation for parallel operation may be easily added to the voltage-sensing circuit, shown by the dotted lines of Figure 6, and consisting of a current transformer and a rheostat. Droop with reactive kva is therefore introduced in the voltage regulator characteristic to allow parallel generators to divide kvar in much the same manner as governor droop allows division of kw load between paralleled generators. A second transformer and rectifiers may be added to accomplish three-phase sensing of the generator voltage. The transformers are connected open delta and, by addition of diodes, the single-phase bridge rectifier is converted to a three-phase bridge. Suitable transformer reconnections will add cross-current compensation to the three-phase sensing system.

A 75-hp induction motor was successfully started by a 150-kw brushless generator set. The maximum voltage dip for this start was 39 percent and the voltage recovered to within 2 percent in slightly over 2 seconds—approximate load of twice rated kva at low power factor. Steady-state voltage regulation of $\pm\frac{1}{2}$ percent has been achieved from zero to rated load at both unity and 0.8 power factor, with ± 5 percent frequency variation, ambient temperature changes of ± 10 C and field temperature changes.

Static regulator is reliable

This static regulator requires negligible maintenance and matches or exceeds the reliability of the brushless exciter-generator. The necessary transformers, resistors and semiconductor rectifier elements match the dependability of the magnetic amplifier when operated at conservative design ratings. Maintenance consists only of periodic inspection and removal of accumulated dirt to assure that normal operating temperatures are not exceeded.

Excellent performance is achieved with a combination of compensation and regulating circuits. This magnetic-amplifier regulator and excitation system was designed for the brushless exciter-generator, although it is not limited to this type of exciter. It may be used with a conventional dc exciter and generator, or as a complete static exciter for generators of small kw rating. Performance of this regulator was designed for commercial application on standard engine-generator sets. Significant improvements in steady-state accuracy and transient performance are possible by further extensions of the basic design principles.

Similar design considerations apply to static exciters for use with conventional generator designs using slip rings. Static exciters have been furnished on generators rated from 10 kw up to 1500 kw. The inductor-alternator excitation system with magnetic amplifier control has been used on generators rated up to 66,000 kw.[2]

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2. "AC Excitation System," J. A. Zimmerman.
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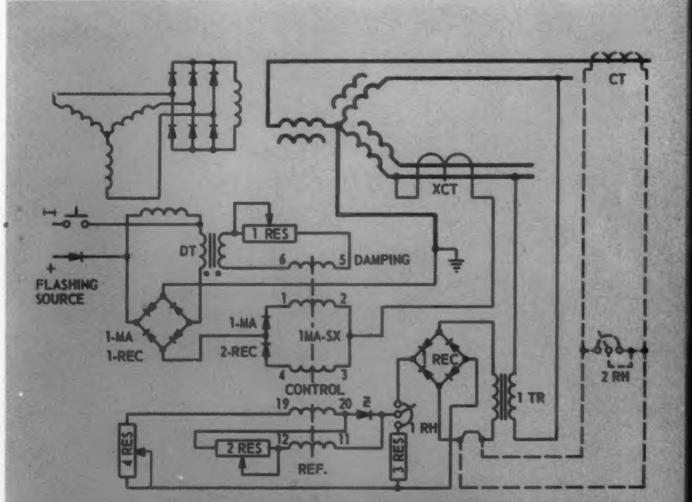
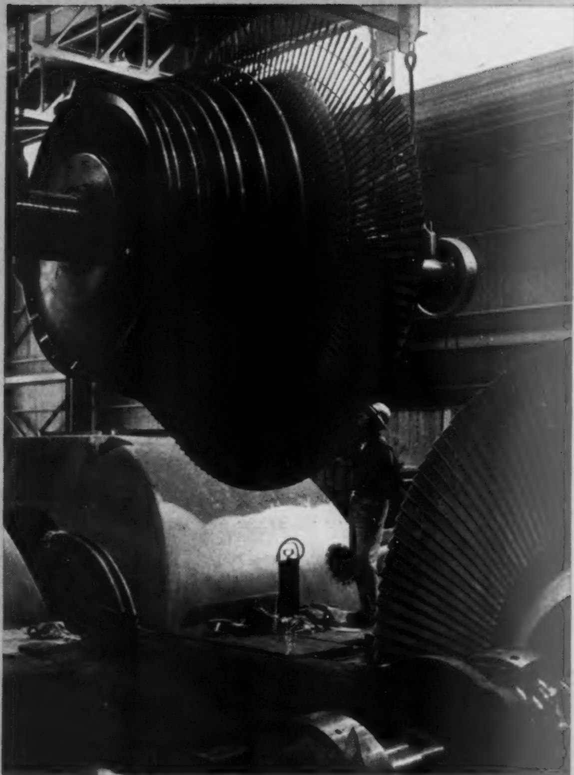
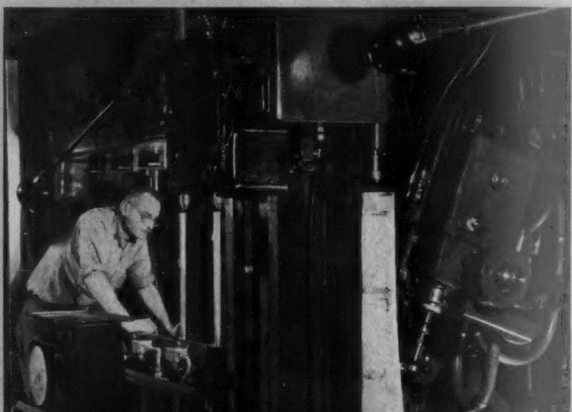


VOLTAGE REGULATOR FOR BRUSHLESS GENERATOR – SCHEMATIC DIAGRAM

DIAGRAM shows complete brushless generator, exciter and regulator system. Dotted lines indicate cross-compensation circuit. (**FIGURE 6**)



HALF of giant low pressure spindle is shown during installation of 321-mw turbine, now in operation. Two of these spindle elements, mounted back to back, exhaust into a single condenser. Tip speeds of the exhaust blades exceed 1400 feet per second at rated 1800 rpm.
Photo courtesy of The Detroit Edison Company



MULTIPLE-SPINDLE blade milling machines, like this four spindle miller, permit machining of complex blade profiles required in modern high capability turbines. Blades shown have 46-inch length, largest in operation. Blade model and cam follower are at right.

BIG BLADES for 300-mw steam flows

by **W. C. FRAZIER**
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Allis-Chalmers Mfg. Co.

Longer exhaust blades enable steam turbine capabilities to keep pace with utility load growth. Bigger blades mean more modern facilities and precise manufacturing techniques.

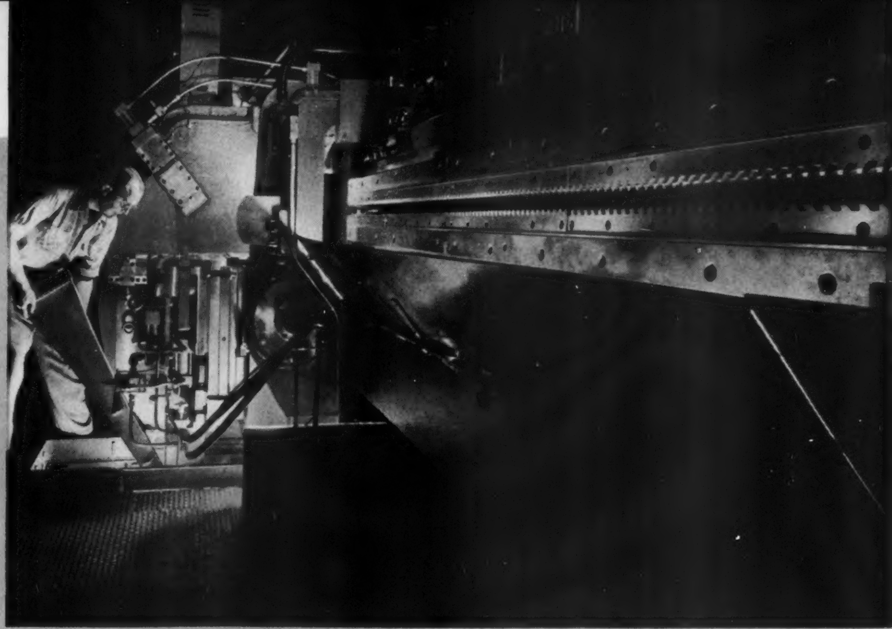
AT THE BEGINNING OF 1959, the nation's generating capacity was nearly 145 million kw, almost double the 76 million kw mark of 1951. During this period ratings of individual steam turbine-generator units have increased until the average unit on order is nearing 200 mw.

Because of the increased steam flows required by these big turbines and the resulting large volumetric flows at the low pressure end, the length of the last row of blades is an important factor in determining the maximum output of the unit. To handle the large volume of low pressure steam efficiently, turbine designers must choose between a greater multiplicity of exhaust flows or larger exhaust areas.

By using many exhaust flows, even the largest steam flows can be accommodated with moderately sized last-row blades. However, if the number of parallel flows can be reduced, the design, construction and operation of a larger unit can be simplified. Fewer parallel flows require less duplication of such parts as cylinders, shafts, bearings, and steam glands. For this reason, longer exhaust blades are designed to provide a greater annular area for handling the increased volume steam flows within economical and practical limits.

Longer blades require precise machining

The introduction of longer blades has, however, brought new problems to the turbine manufacturer. Increasing blade lengths means profiles with greater twisting and tapering so that the desired control of steam flow can be



HORIZONTAL RAM-TYPE BROACH cuts precision root forms for steam turbine blades of any desired length. The 46-inch blade being placed in the machine will be used in 250-mw, 3600/1800-rpm turbine-generator unit.

FOUR MAJOR STEPS in turbine blade production, shown left to right, are rough forged, machined to fit milling fixtures, contours milled, and completed blade with fir-tree root broached and Stellite erosion shield and blade stiffener studs applied.

realized through the blade areas. These carefully contoured profiles must be precisely sized and shaped to extract the maximum work from the steam.

Multiple-spindle milling machines cut these complex contours to the close tolerances required, allowing accurate milling of up to six blades simultaneously.

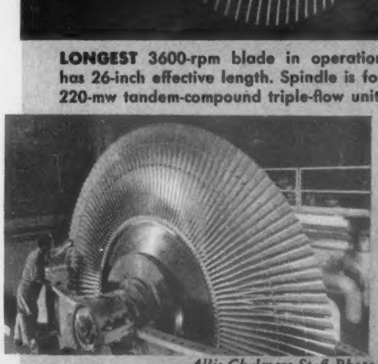
Prior to installation of these multiple-spindle millers, exhaust blades were individually machined, one side at a time, by profile planing and shaping equipment. While the modern milling machines utilize a similar operating principle, with cutting tools hydraulically positioned and guided by a follower on a duplicate blade model, the process is greatly improved and accelerated. The entire blade contour, including platforms for the blade stiffeners, accommodation for the erosion shield and the approximate root platform, is machined in a single operation. In addition to saving production time, the multiple-spindle blade millers turn out more uniformly machined blades.

Blade roots are broached

Blade roots are among the most highly stressed sections of the turbine-generator unit. Since maximum tip speeds are in the supersonic range, the root of a long blade must withstand centrifugal forces in excess of 125 tons. In addition to the high strength blade material required for this loading, exact machining of the root form is essential. This machining operation was formerly accomplished in two steps by first milling and then broaching the blade roots.

An electromechanical, horizontal broaching machine now combines these steps into a single operation, producing a finished root with two quick passes — a roughing

LONGEST 3600-rpm blade in operation has 26-inch effective length. Spindle is for 220-mw tandem-compound triple-flow unit.



INDICATIVE of power growth is 46-inch blade disk in rotating blade vibration test facility.

Allis-Chalmers Staff Photo by Michael Durante

TANDEM-COMPOUND, double-flow, 150-mw steam turbine-generator unit is first of four duplicate machines to be installed at the New Albany Station of the Public Service Company of Indiana. All of the new turbines will use 26-inch exhaust blades.

and a finishing cut. The milling operation is eliminated and tolerances within 0.0005 of an inch are realized. For some blade sizes the ram-type broach is capable of producing a finished root in a single pass.

Vibration studied

Some of the most difficult problems in the design of spindle blades are those concerning blade and disc vibration. The solution of these problems requires extensive testing and development work. A rotating blade vibration test stand is used for experimentally determining the vibration characteristics of various sized blades and discs. It has also been used to "run out" the discs to stress levels simulating actual operating conditions.

The shaft on which the disc is shrunk is driven by a 500-hp steam turbine with a reversing turbine for braking. Leads from barium titanate crystals are cemented to the blades undergoing tests and brought out through the center of the shaft to slip rings. The vibration signal is transmitted to test instruments where it is analyzed.

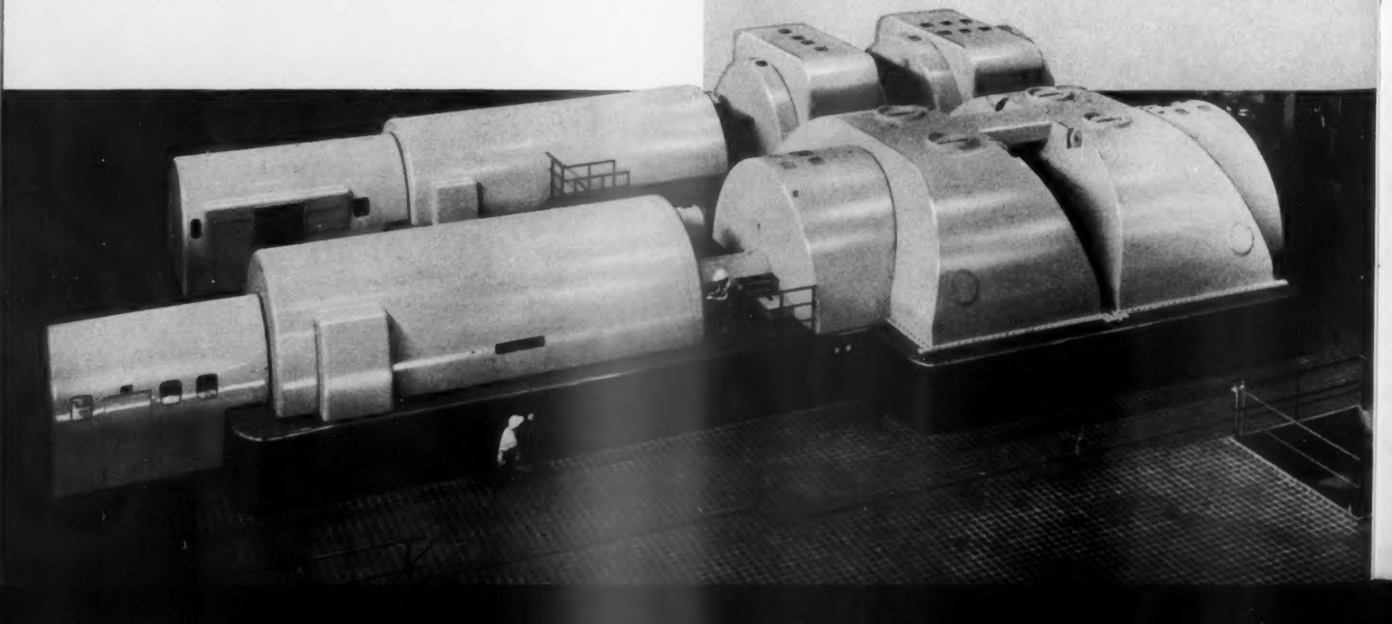
Shrouded and unshrouded blades as well as blades with and without stiffeners are analyzed. Continuous tests and analyses confirm design calculations and afford the best assurance of reliability of the long exhaust blades required by today's high capability steam turbines.

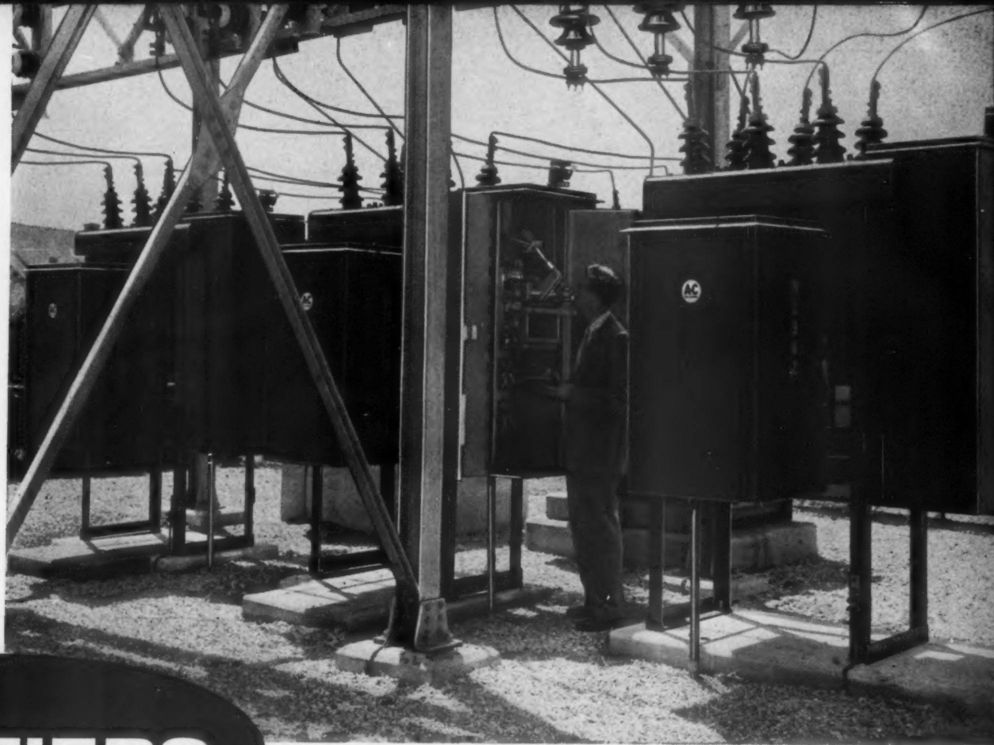
Present-day facilities are more versatile, timesaving and accurate. They enable manufacturers of steam turbines to build the larger generating units necessary for our growing power needs.

BLADE STRESSES, critical speeds, vibration studies and many other computations are performed by modern integrated computer facilities.

ONE OF THE LARGEST power-generating units in service is Detroit Edison's 321-mw Unit 3 at River Rouge Station. It is similar to the 327-mw unit at the Fisk Station of Commonwealth Edison Company in Chicago. Both utilize the new 46-inch exhaust blades.

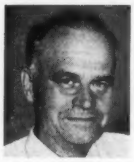
Photo courtesy of The Detroit Edison Company





INSPECTION TIME and maintenance costs are reduced when rectifiers are used for closing solenoid-operated power circuit breakers. **(FIGURE 1)**

RECTIFIERS FOR CLOSING POWER CIRCUIT BREAKERS



by H. B. ASHENDEN
Boston Works
Allis-Chalmers Mfg. Co.

Tests show that some of the newer semi-conductor rectifiers are suitable and possibly preferable for breaker closing applications in locations where batteries are not economically feasible.

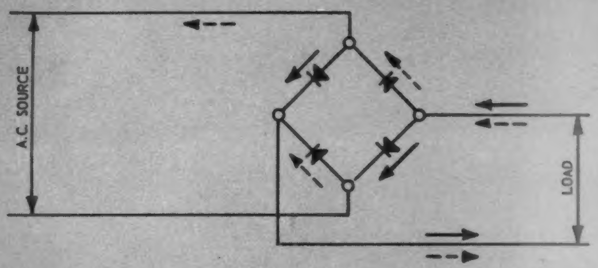
SEVERAL METHODS are now in general use for closing power circuit breakers, but most of the numerous indoor and outdoor breakers rated 15 kv and below are still closed by a solenoid as they have been for many years. In central stations and large substations a large and expensive storage battery has almost invariably been used for all control functions, including breaker closing with a dc solenoid operator.

A dc storage battery is regarded as the most reliable source of control energy, but there are many isolated locations where cost and maintenance expense of large batteries are excessive. In remote locations it is customary to close solenoid-operated breakers with low voltage ac power (usually 230 volts) from a step-down transformer energized by the same primary circuit to which the breaker is connected. Obviously, if the primary circuit fails, the breaker cannot be power closed, but there are many applications where this factor is not a critical consideration.

An ac solenoid might appear to be the best choice for solenoid operators, but it would not be a practical one. The device probably could be made to function but would be relatively large and expensive compared to a dc solenoid of equivalent output. An ac solenoid also draws a large inrush current, and therefore requires a large step-down transformer and heavy copper circuits. It is usually better practice to use the same dc solenoid customarily provided for battery operation plus a suitable rectifier.

Rectifiers provide dependable operation

The rectifier used for circuit breaker closing must be reliable but should be as small and inexpensive as possible. When these devices were first used for energizing circuit breaker closing solenoids over 20 years ago, copper oxide was the best rectifier available and is still the most generally used. Several types of semiconductor rectifiers have



BRIDGE CIRCUIT applies to any type of rectifier — the symbol represents any number of cells connected in series or parallel. Arrows show direction of current for each half cycle. (FIGURE 2)

been satisfactory in experimental use, including selenium, germanium and silicon. None of these newer units have been competitive with copper oxide for circuit breaker application until relatively recently, but the cost of the new devices is decreasing faster than that of the older copper oxide. Investigation has shown that the new, smaller rectifiers are entirely adequate.

All semi-conductor rectifiers offer a relatively low resistance to current flow in one direction, known as the forward direction, and a high resistance to current flow in the opposite or reverse direction. Rectification is not perfect, since there is a small current flow in the reverse direction and a resistance to current flow in the forward direction. The small reverse current is usually of no importance during the momentary duty of circuit breaker closing, but the forward resistance of both copper oxide and selenium, even though small, is a limiting factor in their application. With both germanium and silicon rectifiers the forward resistance is practically negligible, and heating is the limiting consideration.

Semi-conductor rectifier cells are often connected to form a full-wave bridge. Each leg of the bridge may have only one cell or there may be a number of cells connected in series, in parallel, or in series-parallel, depending on current and voltage requirements and the limitations of a single cell. Figure 2 shows the elementary connections for a complete rectifier assembly arranged for full-wave rectification.

Figure 3 is an elementary diagram of a typical control scheme for rectifier closing. The contacts of the control relay 52X are on the input side of the rectifier, and the control is arranged so that contacts are closed to apply voltage to the rectifier only long enough to close the breaker. Closing time is ½ second or less. The total energy handled by the rectifier is, therefore, small, and the losses which appear as heat, which the rectifier must dissipate, are also small. Thus, it is possible to use a much smaller and less costly rectifier than would be necessary for the same current and voltage in continuous-duty applications.

Tests prove rectifier ability

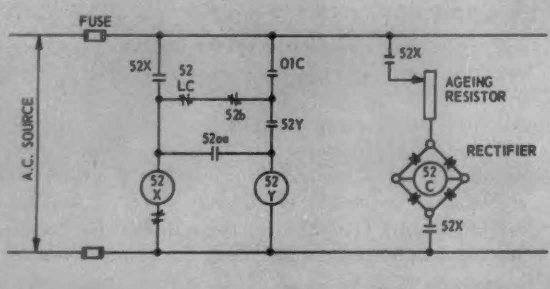
For present-day rectifiers of either the copper oxide or selenium types used with modern breakers, heating does not appear to be a problem if the application is otherwise correct. Tests made with typical combinations of both types with the largest solenoid they are expected to handle have shown that normal breaker operations cause very little rectifier heating. For example, in one case five closing operations, made as rapidly as possible, raised the temperature of the rectifier about 2.5 C, although five immediately repetitive operations are unusual for a breaker in normal service. Probably the most severe duty a rectifier will ever be subjected to is the factory "shakedown" test on a new breaker.

There was no evidence of overheating during test operations, but in order to make certain that these abnormally frequent operations would not damage a rectifier, tests were run on typical rectifiers at maximum control voltage and about 30 percent higher than normal current. Fifty operations made rapidly raised the rectifier temperature appreciably, but for both copper oxide and selenium the maximum temperature was well within safe operating temperatures. The temperature rise for copper oxide was about 15 C and for selenium 25 C.

Copper oxide units used successfully

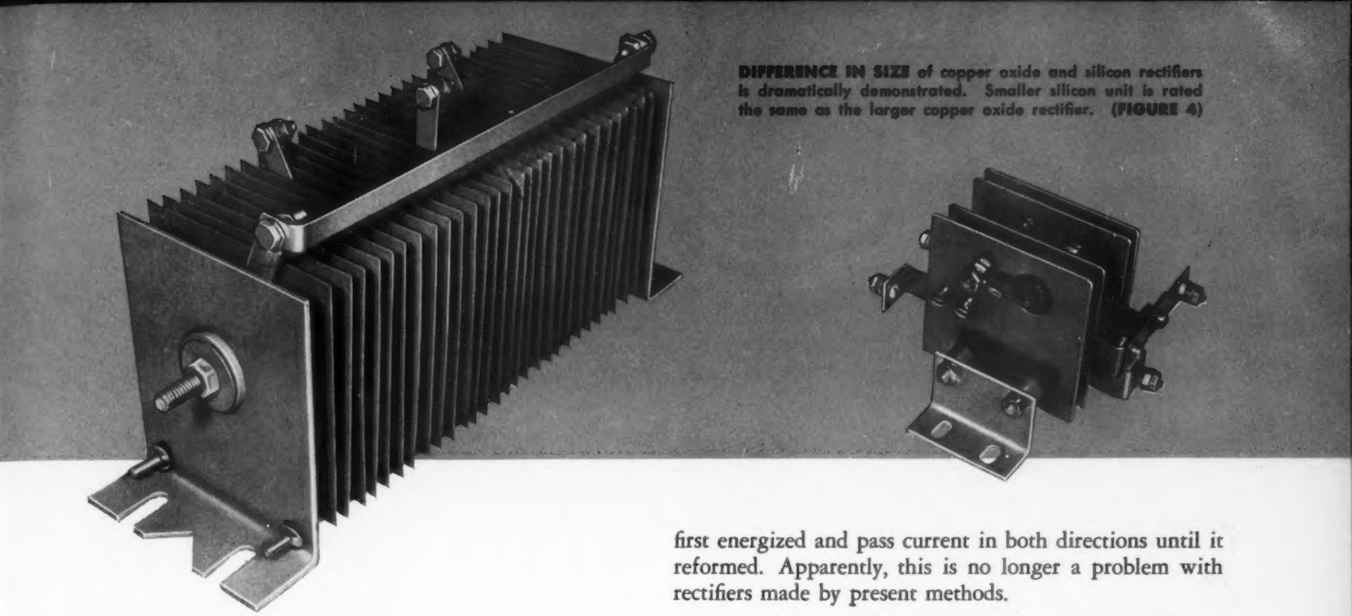
Copper oxide rectifiers were the first units to be applied to circuit breaker closing and are still in general use. Thousands are in service and probably will continue to be used for many years because of their long life. They have some excellent characteristics, such as good thermal capacity and ability to withstand considerable overcurrent and voltage, and are also able to withstand some abuse.

The newer types of rectifiers should be considered in view of the disadvantages inherent in copper oxide units. The characteristic known as "aging," which is an increase in forward resistance with time, is a disadvantage which must be compensated for in circuit breaker application. The rate of increase appears to depend on both the amount of use and the individual rectifier, but the forward resistance will eventually increase, even though the rectifier is idle, and may eventually become approximately double its original value. The rectifier should then stabilize and its characteristics remain constant for many years. Most of them do but a few units have been known to increase in resistance to several times their original value and



○	COIL	52b	BREAKER AUXILIARY SWITCH
⊣⊢	NORMALLY OPEN CONTACT	52C	CLOSING SOLENOID
⊣/⊢	NORMALLY CLOSED CONTACT	52LC	LATCH CHECK SWITCH
01C	CONTROL SWITCH CONTACT	52X	MAIN CONTROL RELAY
52	CIRCUIT BREAKER	52Y	AUXILIARY CONTROL RELAY
52aa	OPERATOR AUXILIARY SWITCH		

MAIN CONTACT 01C is actuated and main control relay 52X closes contacts 52X. Rectifier and solenoid are energized to close the breaker. Late in the closing stroke the limit switch 52aa closes to activate auxiliary control relay 52Y. Normally closed contact 52Y picks up to de-energize main control relay 52X. (FIGURE 3)



DIFFERENCE IN SIZE of copper oxide and silicon rectifiers is dramatically demonstrated. Smaller silicon unit is rated the same as the larger copper oxide rectifier. (**FIGURE 4**)

eventually had to be replaced. In practice, aging is offset by connecting a variable resistor of suitable value in series with the rectifier. This resistance is decreased at intervals as the rectifier ages, until all or most of it is shorted out of circuit, but periodic tests are necessary to determine when and how much to adjust the resistor.

Copper oxide rectifiers are temperature sensitive and can be permanently damaged by overheating. This characteristic is true of all types, but the limiting temperature of copper oxide is considerably lower than that of some of the newer units. The copper oxide also has a considerable negative temperature coefficient limiting its use at low temperatures, can be damaged by long continued high humidity, and is very much larger than some of the newer types of equivalent rating. Nevertheless, copper oxide rectifiers have given excellent service and long life for thousands of circuit breaker closing applications.

Selenium characteristics are improved

Selenium rectifiers have much the same appearance as copper oxide and many of the same characteristics. They will withstand considerable overcurrent for a short time, but no overvoltage. Although forward resistance is higher than for copper oxide, selenium units will withstand higher operating temperatures and have a greatly extended useful temperature range. The selenium-type rectifier has been commercially available for many years but has not been used for circuit breaker closing until relatively recently. Experimental use several years ago showed that they would perform well in this service if sufficient allowance was made for their higher forward resistance. However, because it was necessary at that time to use a large number of plates in series to withstand the voltage, a complete rectifier occupied at least as much space and cost more than available copper oxide of equivalent rating.

Selenium cells or plates which will withstand higher voltages have recently been developed and complete rectifiers, which are smaller, lighter and comparable in cost to copper oxide, are now available.

The selenium rectifier was not considered suitable for circuit breaker closing because of its characteristic of unforming when idle for a long period. That is, it would cease to be a good rectifier for a fraction of a second when first energized and pass current in both directions until it reformed. Apparently, this is no longer a problem with rectifiers made by present methods.

The results of circuit breaker closing tests made on selenium rectifiers which were idle for a year or longer showed some increase in reverse current for the first few cycles; however, the increase was much too small to have any effect on the operation of a circuit breaker. Selenium rectifiers may have the disadvantage of aging in common with copper oxide, but there is reason to believe that they may be affected to a lesser degree. In continuous-duty applications selenium will definitely age, that is, increase its forward resistance, but it does not show much tendency to age when idle. Consequently, in normal circuit breaker operation when the rectifier will be idle most of the time, aging may be negligible over a reasonable life span. However, for the present and until more data are available, it would seem necessary to make some allowance for aging in selenium rectifier applications.

Germanium rectifiers are superseded

Germanium rectifiers became commercially available relatively long after the development of the selenium types, and germanium power rectifiers capable of handling a circuit breaker closing load have been available for an even shorter time. They have some very desirable characteristics, such as practically negligible forward resistance over the normal temperature range, no aging, very small size and hermetic sealing. However, they have practically no thermal capacity and will not withstand much of an overload for more than a fraction of a second. They are temperature limited, since the junction is quite likely to be destroyed at approximately 100 C. In circuit breaker application their ambient temperature should probably not exceed 45 or 50 C.

A germanium rectifier with an adequate peak inverse voltage rating and a continuous-duty current rating equal or close to the peak closing current of a breaker will function satisfactorily to close the breaker, but the cost would be prohibitive. Further consideration of the low forward resistance and the short duration of the peak current indicated that a smaller rectifier cell might be adequate, if mounted on a suitable heat sink. After investigation a size was selected with a cost comparable to copper oxide.

Germanium rectifiers performed well in circuit breaker application tests. Some of the tests were quite severe.

Several hundred operations were performed at 30-second intervals with the rectifier held at 45 C ambient. On the basis of these tests and satisfactory experimental use, a field trial was initiated. However, germanium units were discontinued in circuit breaker application when silicon rectifiers became available at reasonable cost.

Silicon can operate at higher temperature

Silicon rectifiers have all the advantages of germanium, such as small size, no aging and low forward resistance plus a much greater temperature range and a higher voltage per cell. In common with germanium they have very little thermal capacity. Originally high in cost, they are now available at a reasonable price.

Recent experiments show that a silicon rectifier, consisting of four cells mounted on small heat sinks in a full-wave bridge connection, would satisfactorily close a breaker which has a peak closing current several times the continuous-duty rating of the rectifier at the standard maximum 250-volt ac control voltage. A number of tests were conducted including one in which the rectifier was held at 70 C ambient and the breaker was closed repeatedly at 30-second intervals. Although 70 C is a much higher ambient than is ever expected in actual operation, no overheating or damage to the rectifier was evident.

The silicon rectifier is well adapted for circuit breaker application and units are now installed on operating breakers. The absence of aging and the small size are particularly desirable features, since space is often at a premium in switchgear installations. Figure 4 shows the difference in size between a copper oxide unit and a silicon rectifier which will operate the same solenoid. The low forward resistance means that more dc voltage is available at the coil terminals and a higher voltage coil can be used, with a consequent decrease required in the peak closing current.

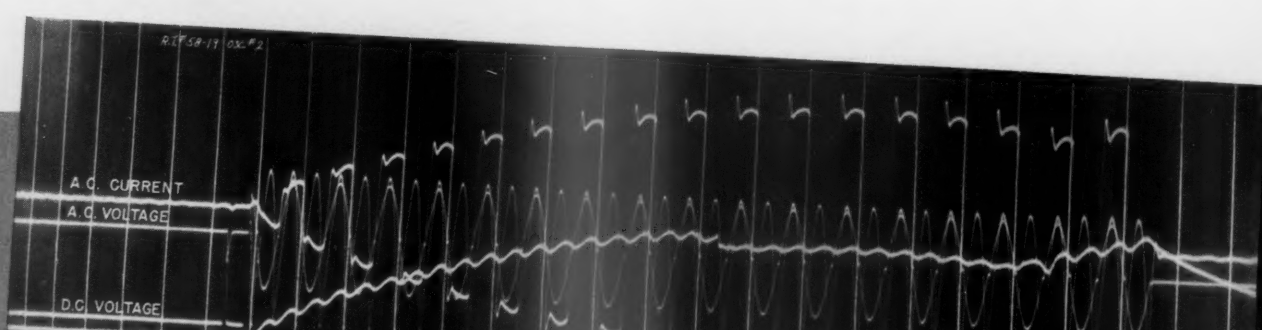
Silicon rectifiers have little thermal capacity and will not stand the abuse that copper oxide is sometimes capable of. For example, during breaker maintenance it is sometimes convenient to make a number of closing operations in rapid succession. Although such operations are not recommended for copper oxide, they usually are not harmful; but more than three or four quickly repeated operations will probably destroy the silicon junction. If many closing operations are performed, it is essential to wait a minute or more between them. It is also possible that mechanical difficulty with a breaker, resulting in sluggish closing, might destroy a silicon rectifier. Recommended protection is a thermal time-delay fuse with a current rating slightly less than the continuous-duty rating of a single rectifier cell. Experimentally, these fuses have performed fairly well. Voltage spikes because of switching may also destroy this type of rectifier. A small capacitor connected across the rectifier will bypass such voltage spikes.

Electrical properties are similar

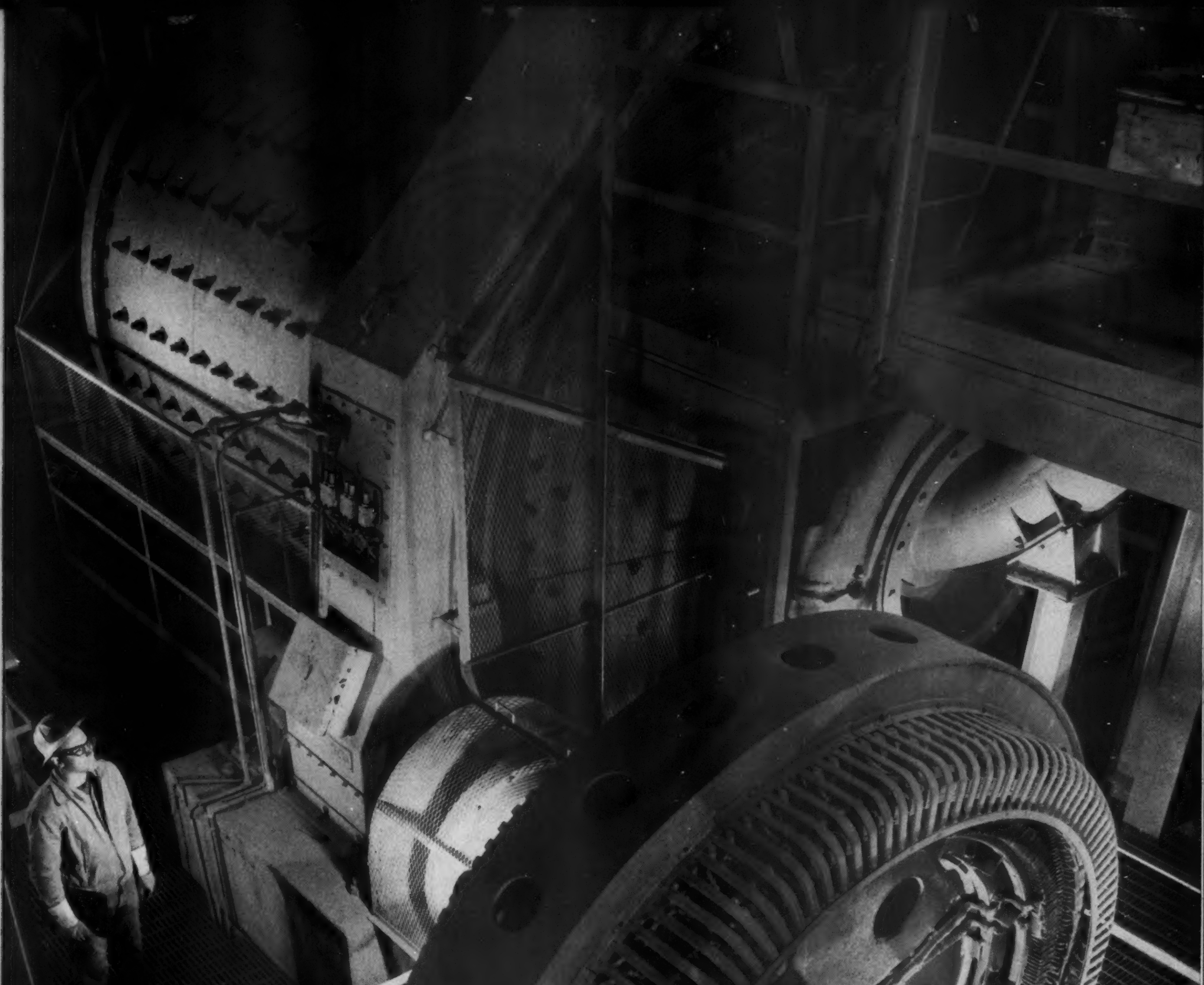
The oscillogram of Figure 5 is a silicon rectifier test record but is typical for all semi-conductor rectifiers. For copper oxide, the trace of dc voltage would show a small reverse voltage below the zero line because of higher reverse current, but is otherwise similar. The dc peak voltage would be less because of greater voltage drop in the rectifier. The ac voltage is a sine wave and the current is very nearly a square wave because of the high inductive load. The dc is very similar to battery output, except that it has a ripple of a few amperes and builds up to its final value in a shorter time. Note the short time that the peak current exists. The vertical lines on the oscillogram represent time in cycles. Time to close, as indicated by the bottom of the dip in the closing current, is about 15 cycles. Current close to the peak value existed for some nine cycles, or about 0.15 seconds.

Silicon rectifiers will probably replace others for circuit breaker closing unless unexpected difficulties develop. There has been no difficulty up to the present, but applications are too few to produce conclusive indications. Silicon units have performed well on tests, and the advantages of no aging, very small size and low forward resistance make them applicable for circuit breaker closing.

The dc solenoid energized by a rectifier from an ac source has been used for over 20 years for closing breakers in locations where the greater reliability and expense of a battery or other stored energy source were not considered necessary or justified. The application of semi-conductor rectifiers for breakers rated 15 kv and less is increasing and the increase will probably continue until a suitable stored-energy source becomes available at a reasonable cost.



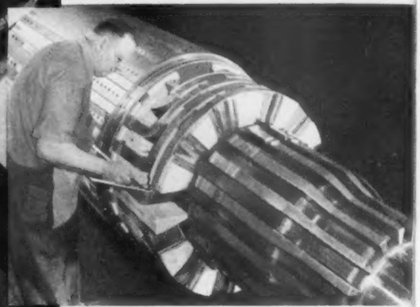
OSCILLOGRAM is typical for all semi-conductor rectifiers with sine-wave input. The dc voltage trace for a copper oxide unit would go slightly below the zero reference because of a higher reversed current. Rectified dc with only slight ripple builds up to final value in shorter time than will battery current. (FIGURE 5)



SYNCHRONOUS MOTOR DRIVES a 13 by 16-foot dry grinding ball mill used to prepare raw feed for a dry process cement plant. Motor rating is 1500 hp, 4160 volt, 160 amp, three-phase, 60 cycle at 180 rpm with 50-volt excitation.

Varying the wound-rotor starting winding resistance allows the unit to come up to speed gradually with low starting kva. Wound rotor's high starting torque eliminates the clutch usually associated with synchronous motor applications. This installation is one phase of the expansion program initiated to meet the Portland cement needs of building and highway construction industries.

A Close Look at LARGE GENERATOR ROTORS



SUPERCHARGED ROTOR for 250-mw cross-compound steam turbine-generator unit uses glass melamine blocking and glass reinforced epoxy premolded channels in the end coil region. **(FIGURE 1)**

by **L. T. ROSENBERG**
Chief Generator Design Engineer
Steam Turbine Department
Allis-Chalmers Mfg. Co.

Significant advances in rotor materials and construction methods are aiding in extending the capabilities of supercharged generators.

SUPERCHARGED COOLING of large steam turbine generators has brought about amazing gains in generator capabilities. Less obvious factors contributing in this progress are improved insulation, advanced construction methods and new alloy steels.

Important progress has been made in rotor insulation. The rotor slot channel insulation is precision molded from epoxy-bonded oriented glass laminate material having great mechanical strength as well as excellent insulating and thermal properties. Recent tests on samples of this material indicated well over twenty times the strength required. The coil end insulation consists of U-shaped glass-epoxy channels premolded to the curvature of the coil ends. The high velocity hydrogen is more effectively confined to the coil ducts by this design than with the earlier phenolic blocking, thus assuring more uniform cooling of the coil end region.

The coil end blocking shown in Figure 1 is of glass mat melamine material which is stronger and thermally more stable than the earlier asbestos phenolic material. The picture illustrates the ease of entry of hydrogen into the bevel edge ducts.

The rotor coil retaining rings that support the coil ends against centrifugal force are forged from nonmagnetic manganese-nickel-chromium austenitic steel. This material responds favorably to cold working, acquiring very high strength by this process while maintaining exceptional ductility. Tests on samples of this material above its yield strength indicate its ability to resist hundreds of overloads without fracture.

In addition to minimizing excitation losses, these nonmagnetic rings help reduce stator end-iron losses and temperatures. Prior to assembly on the rotor, the retaining rings are subjected to a hydrostatic test up to a stress well above that corresponding to maximum overspeed.

Axial slots to carry the windings are milled along the full length of the forgings. Coils are held in the slots with precision-drawn, precipitation-hardened, nonmagnetic steel wedges, as shown in Figure 1. Manufacture and fitting of the slot wedges is an exacting operation. The centrifugal force of the coils acting against the wedges requires the strongest obtainable nonmagnetic material. The wedges are so tough that ordinary machining is very difficult, yet their surfaces must be flat and accurate to insure uniform contact and pressure distribution. To obtain the necessary close tolerances, wedge surfaces are ground to final dimensions. The accuracy of the notch contour in the rotor tooth is achieved by careful checking and maintenance of the rotor milling cutters.

Retaining rings are shrunk on rotor body

Prior to winding the rotor, the end slot wedges are inserted into their slots to insure a smooth shrink fit area for the rotor coil retaining rings. Special jacks hold wedges firmly in running position while the wide shoulders are machined to exact dimensions. The wedges are then carefully identified as to their locations and removed to permit winding.

A heavy interference fit is provided between the rotor body and the coil support ring to insure tightness up to the maximum overspeed. To further lock the rotor coil retaining rings of large 3600-rpm generators against thermal expansion forces, Cr. steel keys are employed in the

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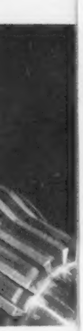


interference fit region. The end disks are firmly held against the expansion forces of the rotor coils by an overhanging lip at the outer edge of the rings and are not in contact with the shaft. This construction affords maximum reliability under all operating conditions.

Forging metallurgy keeps pace

Perhaps the most significant development in rotor manufacture has been the progress in forging metallurgy. Vacuum-poured ingots have become available for even the largest rotor forgings. Figure 2 shows the general type of vacuum pouring equipment now being used by most suppliers in the production of these huge vacuum-poured ingots, which may exceed 200 tons for rotor forgings. Alloy steel forging specifications now include transition temperature* and Charpy impact strength in addition to the usual physical properties.

Test data accumulated in recent months show a steady rise in impact strength and a decline in transition temperatures. Acceptance of specified maximum transition temperatures by the suppliers has made possible the elimination of rotor prewarming.

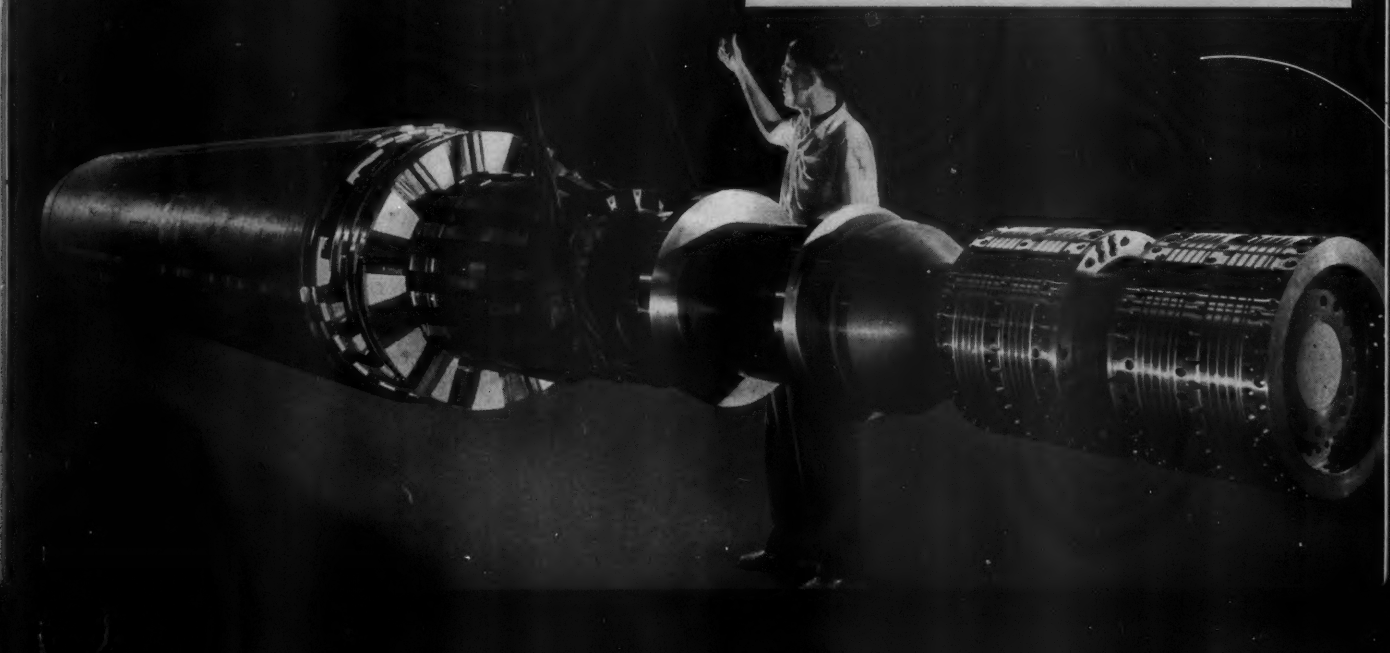
Supercharged rotors require substantial field currents and in the large ratings are equipped with generously proportioned collector rings. Outboard guide bearings are used in these machines for additional support. The rotor is first carefully balanced in the hot balance pit, then assembled in the stator and the guide bearing added. Further balance refinement is then undertaken if necessary. This procedure has proven highly effective.

Along with the great advances in turbine-generator capability made possible by conductor-cooling, there has been considerable parallel progress in materials, design features, and manufacturing techniques. These developments have contributed in great measure toward improved performance while preserving the high degree of reliability needed in today's large turbine generators.

*"Transition temperature" is defined in a proposed American Society of Testing Materials specification for test on forgings as "The temperature at which the fracture appearance of a V-notch Charpy impact specimen is 50 percent fibrous and 50 percent cleavage."

VACUUM CASTING of rotor forging ingots, an outstanding advance in present-day metallurgy, plays important role in manufacture of the high quality forgings needed for large generators. **(FIGURE 2)**
Photo courtesy United States Steel Corporation

READY for installation of coil retaining rings, this 3600-rpm supercharged rotor for large tandem unit is rated 291 mva at 60 psig hydrogen pressure. Rotor incorporates latest improvements. **(FIG. 3)**



by **W. M. TERRY**
Director Engineering Coordination
Allis-Chalmers Mfg. Co.

Engineering department efficiency can be greatly improved by properly "focusing the flow" of information between engineering personnel.

FOCUSING FLOW MAY BE defined as refinement of information moving from one point to another. This focusing of flow occurs as a normal part of good communications between management and the actual design or technical engineer. The personnel and their duties must be considered before this process can be put into action. Engineers in training, experienced technical engineers, supervisory or middle management engineers and top management engineers might be considered as the engineering personnel. While titles vary from company to company, the four classifications exist in most large plants. Other individuals, such as technicians, layout designers, draftsmen and clerical help, may also be involved.

With good communications between engineers, a correct flow of information to other personnel would naturally follow. Normally the engineer would prepare and formulate the information used by the other group.

The information flow among the various types of engineers is shown in Figures 1 and 2. Figure 1 is a line organization communications flow scheme. The top management engineer who is primarily responsible for engineering policy and administrative decisions is at the head of the chart. On the next level is the supervisory or middle management engineer, who has primary project responsibility in administration of projects. The experienced technical engineer, who has no administrative responsibilities but is the head of the technical team, is on the same level. His technical background and know-how are used directly to solve the problem at hand. The engineer in training is on the lower level. This engineer may be a new employe, recently graduated from college or has just completed the company's graduate training course.

Another version, the line and staff communications flow, is shown in Figure 2. On the top level is the top management engineer with a staff position. The supervisory or middle management engineer and the experienced technical engineer are on the secondary level, while the engineer in training is on the lower level. Added to this basic diagram is the operating manager, who has a non-engineering function and is responsible for profit and loss, commercial policy, manufacturing, and the like, as well as engineering. In this diagram the supervisory or middle management engineer reports directly to the operating manager. In large companies this middle management engineer would represent a department chief engineer. Where the company has a number of departments, the top management engineer would represent the staff position of the vice president of engineering, director of engineering, or a similar title. For proper information flow between these individuals, information would move in the directions shown.

Flow is in two directions

In the line organization, policy and project assignments flow from the top management engineer to the supervisory or middle management engineer; the reverse flow consists of project reports. From the supervisory or middle management engineer job assignments flow to the experienced technical engineer; the reverse flow consists of job reports. From the experienced technical engineer training information and task assignments flow to the engineer in training; the reverse flow consists of "requests for advice" and task reports. In addition, there are two indirect flows shown by the arrows. The first is from the

experienced engineer to the top management engineer and consists of briefings and special reports. The second is from the supervisory or middle management engineer to the engineer in training and consists of training information and personal guidance.

In staff organizations, the top management engineer passes information to the supervisory or middle management engineer in a staff capacity. This information usually consists of policy guidance and explanations. The reverse flow is limited or condensed project reports. Duplicating the line organization, briefings and special reports information flow from the experienced technical engineer to the top management engineer to the operating manager and consist of policy and project recommendations. Requests for policy and project advice form the reverse flow.

When the supervisory or middle management engineer passes on a job assignment to the experienced technical engineer he should attempt to define specifically the objectives of the job assignment. Boundaries should be defined, tentative solutions to the problem suggested, and limitations pointed out on proposed methods. He is focusing his information flow. If he simply breaks down a project into parts, calls in the experienced engineer and says, "Here's the next job," the supervisory engineer is not contributing toward the solution of the problem but is simply passing information on in a parallel flow manner. This is not particularly harmful, but the results are generally neutral.

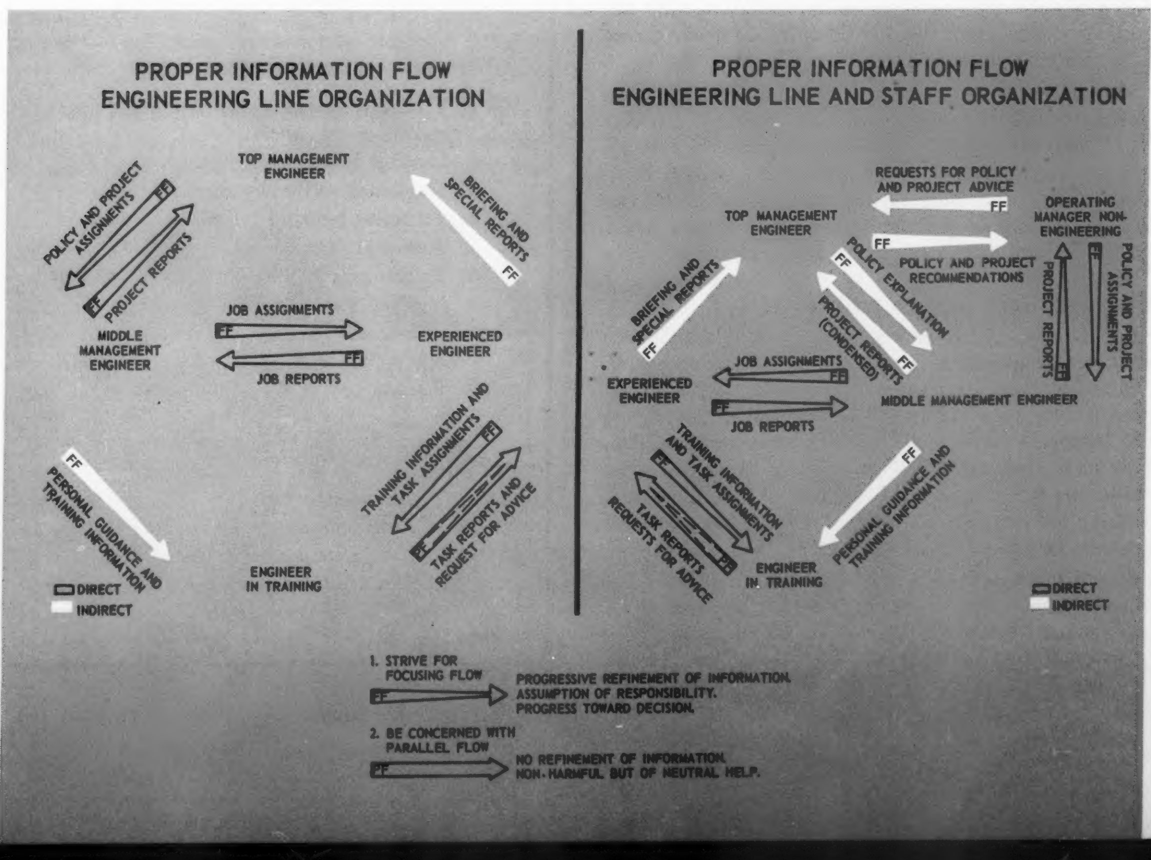
On the other hand, other types of flow are possible, one of which might be termed confusion flow. In this case the job assignment is outlined without regard to boundaries, limitations or policy background. Irrelevant information which does not tie in directly with the job may also add to the confusion, and leave the experienced engineer with a very hazy concept of what is expected of him.

Log jams create high pressure situations

A fourth type of information flow can result in a log jam. Information is dammed up and only a few shreds or leaks are passed on. The person down the line, therefore, obtains no clear idea of what is expected from the limited information he receives. The reverse flow is very likely to be just as narrow and noncontributory to problem solution. Log jamming produces a high pressure approach chosen by some individuals in the interest of what is mistakenly considered as efficiency. However, in an engineering area log jamming definitely results in no progress. The pressure builds up but the work content is nil.

With proper focusing in both directions between individuals, the progressive refinement of information as it passes along has to end up in a needle-point solution.

One area in the diagram where parallel flow will generally be experienced is in the flow of information from the engineer in training to the experienced technical engineer. One measure of the evolution of an engineer in training to an experienced technical engineer is to see the information flow change from a parallel condition to a focusing condition. In other words, the engineer in training begins to assume responsibility and thereby indicates that he is developing into an experienced engineer.



Flow is determined by job content

The differences in job content of each of the four engineering areas affect communication needs. There are four major classifications of information flow:

a) Written internal company communications
b) Spoken internal company communications
c) Written external communications
d) Spoken external communications

If only the various types of internal written communications are considered, the engineer faces a real problem. All are necessary, since the engineer must have full information to do the job that is required. It is important, therefore, that the information be brief and concise, so that it can be quickly assimilated and interpreted by different engineers in essentially the same manner. Generally, formal procedures should be adopted to make certain that this information is:

1. Available
2. Up to date
3. To the point

Standards engineer is needed

It is generally recognized that this information should be compiled by engineers. However, it is usually to the advantage of a company that a standards engineer position be established in even moderately sized engineering departments to index and publish engineering information in a useful manner.

Often the pressure of business in productive organizations makes it difficult to keep internal written communications up to date. If information is not systematically brought up to date, the result will be a loss of teamwork within the organization because individual engineers will be working from a different basis. Design manuals in the hands of individual engineers will be marked up with corrections, extensions or deletions as each individual chooses. Clear written communications will not be available.

Written internal engineering communications are the heart of an effective engineering department. The spoken word is soon lost and the daily decision made on a specific engineering job is filed away with the engineering drawings. Only by incorporating decisions into written internal communications or engineering standards will past experiences be useful for the solution of future problems.

Easy way may lead to pitfalls

One common pitfall in engineering communications is burdening engineers with a mass of irrelevant data. Sending the engineer a great mass of literature, such as books, technical bulletins and magazines, that does not tie in with the engineer's current project or job assignment will confuse more than aid him. The engineer may assume that he is expected to read and assimilate all this information because it comes from management. In so doing he delays his current job assignment.

If the job or work assignment is carefully spelled out in a focusing flow manner, the engineer will then search out all the pertinent data to help him achieve his solution. Analysis of this data alone will keep the engineer busy.

Written internal communications include:

1. Engineering standards
2. Design manuals
3. Process specifications
4. Material specifications
5. Engineering drawing standards
6. Engineering and design reference books
7. Engineering training manuals
8. Engineering memoranda
9. Engineering, development and research reports
10. Performance data reports
11. Office procedures
12. Engineering specifications
13. Company stock indexes and standard parts
14. Engineering assignments
15. Cost studies
16. Comparison evaluations
17. Patent disclosures
18. Engineering and development budgets
19. Engineering and development expense reports
20. Company financial reports

Spoken internal communications include:

1. Person to person contacts
2. Committees
3. Group discussions
4. Seminars
5. Training courses

Written external communications include:

1. Technical articles, either by company personnel or by others
2. Catalogs and catalog files
3. Magazines and newspapers
4. Technical bulletins
5. Technical libraries
6. Translations of foreign technical articles
7. Industry and American standards
8. Individual customer requirements and specifications
9. Patents

Spoken external communications include:

1. Technical meetings
2. Industry committees
3. Outside consultants or specialists
4. Engineering presentations by vendors of materials or components

Modern management should concentrate on defining and describing the problem at hand and leave the data gathering to the engineer. If management engineers want to clear their own desks, engineering information should be sent to the library or filed where it will be available if needed.

Engineers do have a tendency to "rathole" important technical data without malice aforethought. In so doing, they bury it to the disadvantage of other engineers. If this information is given to the standards engineer to sort, he can place it in the proper engineering reference books, standards, design manuals, or the like.

Honest cost data needed by engineer

Giving the engineers reasonable cost data with a clear explanation of how the costs are derived, whether it be manufacturing cost data or material costs, will help him in his work. Figures "guess-estimated out of the air" do not appeal to engineers who are used to being able to check and cross check their engineering calculations. If reasonable figures aren't available, don't dream them up. An engineer should be assigned, if necessary, to help manufacturing or purchasing obtain proper information.

Engineers, surprisingly enough, are generally quite interested in their company's financial picture. A large percentage of engineers understand such financial terms as "price to earnings ratio," "return on sales," "return on capital invested," "return on net worth" and similar financial terms. Let an engineer in on financial problems — he may be instrumental in improving the profit picture.

When policy decisions are being made at the top level, experienced technical engineers are often allowed to participate in briefings to clarify and explain the engineers' suggested solutions. This, however, involves a responsibility on the part of the engineer to make his explanations of complex technical matters in nontechnical language to management. Management decisions are usually on a "go" or "no-go" basis and cannot be weighted down by twenty-two pages of technical data appendices.

Clear appraisal of ideas saves time

If engineers come up with recommendations for new products or new developments which are technically feasible but do not fit in with company policy or cannot be acted upon at that time because of financial limitations, such as the requirements for substantial capital expenditures to produce the new product, it is best not to dodge the issue by becoming engineering critics and questioning to the most minute calculation all of the data presented. The engineer will start off by working many long hours to answer in detail each question and will end up frustrated as he slowly recognizes that action on his recommendation is not dependent on engineering answers but on time only — which may stretch to infinity.

Here is a marvelous opportunity to communicate company policy to the engineer or to explain why the undertaking cannot be initiated at this time because the money just isn't in the till. The engineer will listen sympathetically and just might take that opportunity to advance some original cost saving ideas of his own that, if applied to the business, might put some money in the till and render the engineer's current proposal financially feasible.

There is no greater sense of satisfaction to an engineer than the completion of a complex engineering report complete with recommendations for action. However, satisfaction changes to frustration as days go by and he learns that the report is still on the boss's desk and in the pile.

If we are to do an effective communications job between engineers, and between engineers and management, we have only to accomplish the three following steps:

a) Practice focusing information flow both down and up through the engineering organization.

b) Make certain that written engineering information is easily available, up to date, and to the point.

c) Don't separate engineers and management by assuming that only technical information is the province of the engineer and financial and policy information the sole province of management. Let them intermix at every convenient opportunity.

Following this program, the right information will get to the right man at the right time. An engineering department will become more effective and the engineers will be on the management team.

Vibration Characteristics of Flyball Governors

GOVERNOR gets final test and inspection just prior to assembly on 3600-rpm turbine of 250-mw turbine-generator unit. (FIGURE 1)

by R. D. BAIRD
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Allis-Chalmers Mfg. Co.

A mathematical approach to steam turbine governor design characteristics is a vital part of modern power system studies.

THREE IMPORTANT GOVERNOR characteristics of concern to steam turbine design engineers are the governor natural frequency, valve travel per percent speed change, and governor strength. The governor natural frequency is of particular interest, although the other two characteristics are developed for completeness and to show their interdependence.

The governor natural frequency exhibits several interesting properties and can be analyzed by considering the schematic drawing shown in Figure 2.

The motion is obtained from Lagrange's equation (1) after determining the kinetic and potential energy.

$$(1)\qquad \frac{d}{dt}\left(\frac{\partial T}{\partial q'}\right)-\frac{\partial T}{\partial q}+\frac{\partial V}{\partial q}=0$$

The total kinetic energy may be written as

$$(2)\qquad T=T_{f.b.}+T_s\,T_v$$

where

$$(3)\qquad T_{f.b.}=\frac{w}{g}\left[l^2\alpha'^2+\Omega^2\,(c+l\sin\alpha)^2\right]$$

$$(4)\qquad T_s=\frac{1}{6}\,\frac{w_s}{g}\left[l^2\alpha'^2+\Omega^2\,(C+l\sin\alpha)^2\right]$$

$$(5)\qquad T_v=\frac{2\,W}{g}\,l^2\alpha^2\sin\alpha'^2$$

The total potential energy is given by

$$(6)\qquad V=V_{f.b.}+V_s+V_v$$

where

$$(7)\qquad V_{f.b.}=-2wl\,(\cos\alpha_1-\cos\alpha)$$

LIST OF SYMBOLS

T . . . . kinetic energy
V . . . . potential energy
α_1 . . . . governor angle at zero speed
α . . . . governor angle
α_o . . . . mean governor angle
η . . . . angular amplitude of vibration
W . . . . valve wt.
w . . . . flyball wt.
w_s . . . . spring wt.
k . . . . spring constant
F_1 . . . . initial spring tension
Ω . . . . governor speed
S . . . . governor strength
ξ . . . . valve travel
f_n . . . . governor natural frequency subscripts
v . . . . valve
f.b. . . . . flyball
s . . . . spring
′ . . . . differentiation with respect to time

$$(8)\quad V_s = 2\,F_1\,l\,(\sin\alpha - \sin\alpha_1) + 2\,k\,l^2\,(\sin\alpha - \sin\alpha_1)^2$$

$$(9)\quad V_v = -2\,l\,W\,(\cos\alpha_1 - \cos\alpha)$$

If the appropriate values of T and V are substituted in equation (1), the equation of motion may be written as

$$\begin{aligned}(10)\quad &\alpha''\left[\frac{2}{g}(w+w_{s/6})\,l^2 + \frac{4\,W}{g}\,l^2\sin^2\alpha\right] \\ &+\alpha'^2\left[\frac{4\,W}{g}\,l^2\sin\alpha\cos\alpha\right] + \sin\alpha\cos\alpha\left[4k\,l^2 - \frac{2\,l^2\Omega^2}{g}(w+w_{s/6})\right] \\ &-\cos\alpha\left[\frac{2\,l\,C\Omega^2}{g}(w+w_s/_6) + 4\,k\,l^2\sin\alpha_1 - 2\,F_1\,l\right] \\ &-\sin(2\,l\,W+w) = 0\end{aligned}$$

If we think of the governor as performing small oscillations about the mean angle, α, then

$$(11)\quad \alpha = \alpha_o + \eta$$

where η is the small angle of oscillation.

With this substitution, equation (10) reduces to

$$\begin{aligned}&\eta''\left[\frac{2}{g}(w+w_{s/6})\,l^2 + \frac{4\,W\,l^2}{g}\sin^2\alpha\right] \\ &+\eta\left\{(\cos^2\alpha_o - \sin^2\alpha_o)\left[4\,k\,l^2 - \frac{2\,l^2\Omega^2}{g}(w+w_{s/6})\right]\right. \\ (12)\quad &+\sin\alpha_o\left[\frac{2\,l\,c\Omega^2}{g}(w+w_{s/6}) + 4\,k\,l^2\sin\alpha_1 - 2\,F_1\,l\right] \\ &\left.-\cos\alpha_o\,[2\,l\,(W+w)]\right\} + \sin\alpha_o\cos\alpha_o\left[4\,k\,l^2 - \frac{2\,l^2\Omega^2}{g}(w+w_{s/6})\right] \\ &-\cos\alpha_o\left[\frac{2\,l\,c\Omega^2}{g}(w+w_{s/6}) + 4\,k\,l^2\sin\alpha_1 - 2\,F_1\,l\right] \\ &-\sin\alpha_o\left[2\,l\,(W+w)\right] = 0\end{aligned}$$

By considering the equilibrium of the governor in steady motion, then

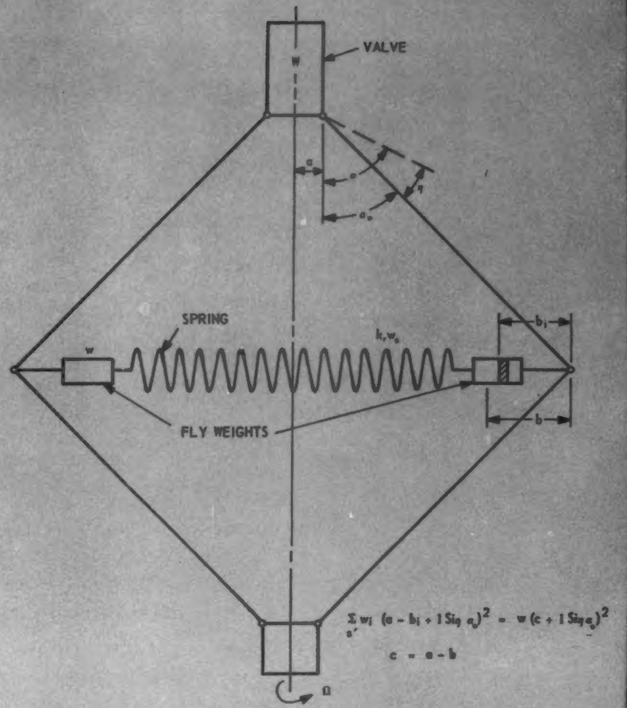
$$\begin{aligned}(13)\quad &\frac{(w+w_{s/6})}{g}\Omega^2(c+l\sin\alpha_o) + \frac{W+w}{\cos\alpha_o}\sin\alpha_o \\ &= F_1 + 2\,l\,k\,(\sin\alpha_o - \sin\alpha_1)\end{aligned}$$

and

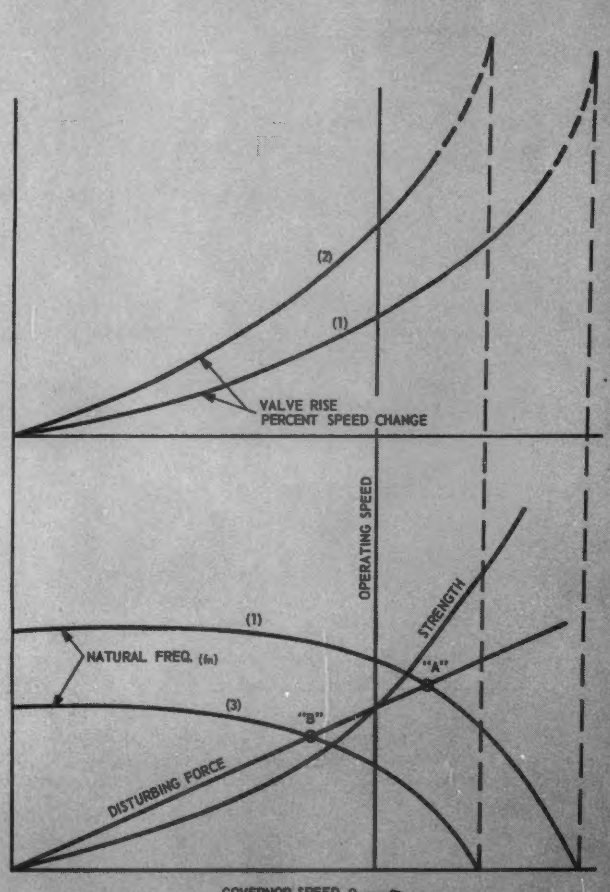
$$\begin{aligned}(14)\quad &\sin\alpha_o\cos\alpha_o\,[4\,k\,l^2 - 2\,l^2\,(w+w_{s/6})\Omega^2/g] - \cos\alpha_o \\ &\left[\frac{2\,l\,c\,\Omega^2}{g}(w+w_{s/6}) + 4\,k\,l^2\sin\alpha_1 - 2\,F_1\,l - 2\,l\sin\alpha_o\,(w+W)\right] = 0\end{aligned}$$

Equation (12) may be simplified with these expressions to obtain

$$\begin{aligned}(15)\quad &\eta''\left\{\frac{2}{g}(w+w_{s/6})\,l^2 + \frac{4\,W\,l^2}{g}\sin^2\alpha_o\right\} \\ &+\eta\left\{\cos^2\alpha_o\left(4\,k\,l^2 - \frac{2\,l^2\Omega^2}{g}(w+w_{s/6}) - \frac{2\,l\,(W+w)}{\cos\alpha_o}\right)\right\} = 0\end{aligned}$$



GOVERNOR shown schematically provides basis for analyses of the characteristics needed for design of modern governors. **(FIGURE 2)**



CALCULATED governor characteristics provide valve rise, frequency and governor strength — the essential data needed for design. **(FIGURE 3)**

This equation is for simple harmonic motion and the frequency is given by

(16)
$$f_n = \frac{1}{2\pi}\sqrt{\frac{\cos^2\alpha_0\left[k\,g-\Omega^2\,(w+w_{s/6})\right]-\frac{(W+w)\,g}{l\cos\alpha_0}}{(w+w_s/6)+2W\sin^2\alpha_0}}$$

If ξ is the valve travel defined by

(17) $$\xi = 2\,l\,(\cos\alpha_1-\cos\alpha)$$

then the valve travel per percent speed change is given by

(18)
$$\frac{d\xi}{d\Omega/\Omega} = \frac{d\xi}{d\alpha}\;\frac{d\alpha}{d\Omega/\Omega}$$

using equations (14) and (17) we obtain

(19)
$$\frac{d\xi}{d\Omega/\Omega} = 4\left(\frac{fd}{fn}\right)^2\left[\frac{(c+l\sin\alpha_0)\,\sin\alpha_0\cos\alpha_0}{1+\frac{2\,W}{(w+w_{s/6})}\sin^2\alpha_0}\right]$$

where Ω is replaced by its equivalent 2π fd.

Substituting for f_n from equation (16), the equation (19) becomes

(20)
$$\frac{d\xi}{d\Omega/\Omega} = \frac{4(w+w_{s/6})\;(c+l\sin\alpha_0)\;\sin\alpha_0\cos\alpha_0}{\cos^2\alpha_0\left[\frac{2\,k\,g}{\Omega^2}-(w+w_{s/6})\right]-\frac{(W+w)\,g}{l\cos\alpha_0\Omega^2}}$$

The governor strength is defined as the force exerted at the valve if it were held fixed and the speed changed one percent. This force would be

(21) $$\frac{w+w_{s/6}}{g}\;(c+l\sin\alpha_0)\Omega^2(1.005^2-.995^2)$$

From the geometry of the governor the strength is expressed as

(22) $$S = \frac{w+w_{s/6}}{g}\;\frac{1}{\tan\alpha_0}\;(c+l\sin\alpha_0)\Omega^2(.02)$$

The governor properties as represented by equations (16), (19) and (22) are shown in Figure 3. Here two governors are compared, one having its resonant point above operating speed, the other having its resonant point below the operating speed.

The flyball weights and hence the strength have been held essentially constant in this comparison. The higher natural frequency is attained by reducing the valve weight or by increasing the spring constant.

The governor natural frequency decreases until a speed is reached where the spring force cannot overcome the centrifugal force and the natural frequency is zero. This characteristic is shown by equation (16).

Since the governor is driven from the main turbine shaft through reduction gears, the governor disturbing force is a linear function of governor speed.

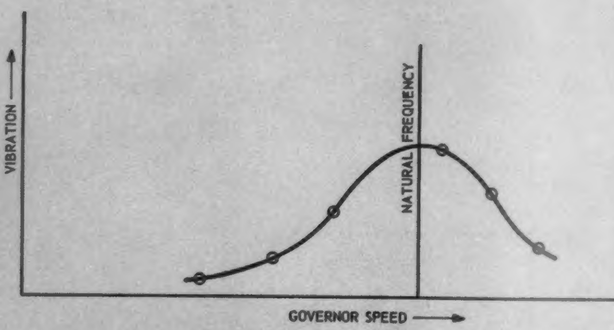
Frequency curve (1) shows a governor of "high" natural frequency whose resonant point "A" is above the operating speed curve (2) shows a governor with a lower natural frequency whose resonant point "B" is below operating speed. In this latter case a phase shift takes place which is undesirable from a control standpoint.

The corresponding valve rise curves are shown for the two governors. The higher frequency governor has a lower valve rise per percent speed change.

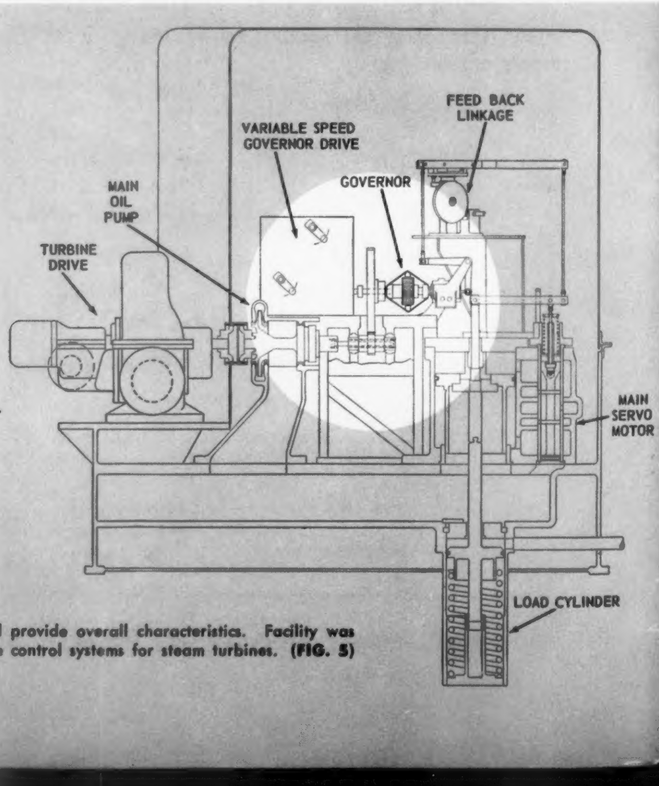
A typical vibration curve obtained on a governor test stand is shown in Figure 4.

Tests were run with various combinations of spring constants and valve weights. In all cases the calculated values were within a few percent of the measured values.

While the governor plays an important role in turbine regulation, it is just one element in a complex control system. The complete control system, if linearized, can be handled by mathematical analysis. However, when taking into account non-linearities the analog computer is used.



ACTUAL TEST VALUES, showing resonance phenomena as determined on test stand, substantiate calculated values. **(FIGURE 4)**



NEW GOVERNOR TEST STAND will provide overall characteristics. Facility was designed for development of complete control systems for steam turbines. **(FIG. 5)**

Silicone rubber on test in Turbine-Generator Insulation Laboratory.

Applied Research
Advances Silicone Rubber Into High Voltage Class

Testing and process developments are now making the use of silicone-rubber insulation for high voltage motor and generator stators a reality. High voltage imposes additional demands on insulation for exceptional dielectric and physical properties. Assurance that these demands can be met are obtained only by long and thorough laboratory testing.

Semi-inorganic silicone rubber is a highly stable resilient material with a combination of properties which are well suited for high voltage insulation. It has excellent dielectric strength and resistance to dielectric fatigue. Its corona resistance is exceptional, approaching that of mica. Being rubbery in nature, it is ideally suited to provide the necessary elastic properties needed for large machine operation. In addition, thermal and chemical stability of this insulation are such that its properties are practically unchanged after long exposure to heat and other adverse service conditions.

Operating experience with silicone-rubber (*Silco-Flex*) insulation has been accumulating over the past five years on hundreds of large motors in the medium voltage range. This insulation has found particular application in adverse service locations where its chemical stability and low water absorption have eliminated the need for conventional protective enclosures. The service experience accumulated to date has been very favorable, and has confirmed earlier laboratory evaluations of silicone rubber as electrical insulation.

Recently, high voltage silicone-rubber-insulated stator windings in the 10-15 kv range have been built and placed into operation. As service experience is accumulated on these higher voltage windings, it is expected that the use of silicone-rubber insulation will extend more and more into the larger high voltage motor and generator designs.

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